IMPROVING THE EFFICIENCY OF PHYSICAL EXERCISES FOR KNEE USING BIOFEEDBACK

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IMPROVING THE EFFICIENCY OF PHYSICAL EXERCISES FOR KNEE USING BIOFEEDBACK

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ABSTRACT

IMPROVING THE EFFICIENCY OF PHYSICAL EXERCISES FOR KNEE USING BIOFEEDBACK

Impairments occurred in the knee result in the decline of the quality of daily activities such as walking, running, sitting, and standing. Depending on the level of impairment, physical exercises are subscripted to regain strength, flexibility, and range of motion. The efficiency of the exercises can be improved by supplying a feedback mechanism during the exercises. Meanwhile, some improvements can be obtained when the knee joint range of motion is assessed during the exercises. The development of automated systems having feedbacks and motion assessments is gaining increased demand.

This thesis work aims to improve the efficiency of physical exercises for the knee by quantifying the knee joint range of motion with the use of two micro-electro-mechanical orientation sensors, and by giving audio feedback by playing predetermined dialogues with the use of an audio player module. Fifteen volunteers are enrolled to analyze the effectiveness of the audio feedback on three physical exercises namely sit-to-stand, squat, and seated leg flexion-extension.

The Wilcoxon rank-sum test results for seated leg flexion-extension exercise, sit-to-stand, and squat exercise shows that the addition of audio feedback shows a statistically significant difference in sit-to-stand ($p=.01$) and squat exercises ($p<.001$) but not in seated leg flexion-extension exercise ($p=.15$). The System Usability Scale (SUS) results show that exercise with audio feedback (SUS score=83.0) has a higher score than exercise without audio feedback (SUS score=72.2), but this increase is not statistically significant ($p=0.14$). The addition of audio feedback in closed chained exercises may increase the efficiency of the physical exercises. This improvement may be seen more drastic in the exercises that do not end with the movement of locking the knee in full flexion or extension. Future studies are planned to compare the designed system with video-based feedback systems used in physical therapy and to examine the effects of audio feedback on knee-based physical therapy with volunteers requiring physical rehabilitation rather than healthy volunteers.

ÖZET

DİZ İÇİN FİZİKSEL EGZERSİZLERİN VERİMLİLİĞİNİN BIOFEDBACK KULLANILMASININ ARTIRILMASI

Dizde oluşan bozukluklar yürüme, koşma, oturma, ayakta durma gibi günlük aktivitelerin kalitesinin düşmesine neden olur. Bozulma düzeyine bağlı olarak, güç, esneklik ve hareket açıklığını geri kazanmak için fiziksel egzersizler yapılır. Egzersizler sırasında geri bildirim sağlanarak egzersizlerin verimliliği artırılabilir. Egzersizler sırasında diz eklemi hareket açıklığı değerlendirildiğinde bazı gelişmeler elde edilebilir. Geri bildirimlere ve hareket değerlendirmelerine sahip otomatik sistemlerin geliştirilmesi artan talep görmektedir.

Bu tez çalışması, iki adet mikro-elektro-mekanik oryantasyon sensörünün kullanımı ile diz eklemi hareket açıklığını ölçerek ve bir ses oynatıcı modülü ile önceden belirlenmiş diyalogları çalarak sesli geri bildirim vererek diz için fiziksel egzersizlerin verimliliğini arttırmayı amaçlamaktadır. Otur-kalk, çömelme ve oturarak bacak fleksiyonu-ekstansiyonu olmak üzere üç fiziksel egzersizde sesli geri bildirimin etkinliğini analiz etmek için on beş gönüllü kaydedildi.

Oturarak bacak fleksiyon-ekstansiyon egzersizi, otur-kalk ve çömelme egzersizi için Wilcoxon sıra toplamı testi sonuçları, sesli geri bildirimin eklenmesi, otur-kalk ($p=.01$) ve çömelme egzersizinde ($p<.001$) istatistiksel olarak anlamlı bir fark olduğunu ama oturarak bacak fleksiyon-ekstansiyon egzersizinde istatistiksel olarak anlamlı bir fark ($p=.15$) göstermektedir. Sistem Kullanılabilirlik Ölçeği (SKÖ) sonuçları, sesli geri bildirimli egzersizin (SKÖ puanı = 83.0) sesli geri bildirimsiz egzersizden daha yüksek puana sahip olduğunu (SKÖ puanı = 72.2) göstermektedir, ancak bu fark istatistiksel olarak anlamlı değildir ($p=.14$). Kapalı zincir egzersizlerde sesli geri bildirimin eklenmesi, fiziksel egzersizlerin verimliliğini artırabilir ve dizin tam fleksiyon veya ekstansiyonda kilitleme hareketi ile bitmeyen egzersizlerde bu iyileşme daha şiddetli görülebilir. Gelecekteki çalışmalar, tasarlanan sistemi sağlıklı gönüllülerden ziyade fiziksel rehabilitasyona ihtiyaç duyan gönüllülerle sesli geribildirimin üzerindeki etkilerini incelemek için planlanmaktadır.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS iv

ABSTRACT v

ÖZET vi

LIST OF FIGURES ix

LIST OF TABLES xi

LIST OF SYMBOLS/ABBREVIATIONS xii

1. INTRODUCTION 1

1.1. AIM OF THE STUDY 1

1.2. ANATOMY AND MOVEMENT OF THE KNEE 1

1.3. KNEE INJURIES AND TREATMENT 3

1.4. PHYSICAL EXERCISES FOR KNEE 4

1.5. ASSESSMENT OF KNEE MOTION DURING EXERCISES 5

1.6. BIOFEEDBACK IN EXERCISES 8

1.7. AIM AND OBJECTIVES OF THE CURRENT THESIS WORK 12

2. MATERIALS & METHODS 14

2.1. STUDY POPULATION 14

2.2. KNEE MOTION DETECTING AND AUDITORY BIOFEEDBACK GENERATING HARDWARE 14

2.2.1. Quantification of Knee movement 19

2.2.2. Storing of Knee Movement Data 19

2.2.3. Audio Player Module and Audio Files 22

2.3. PLACEMENTS OF THE SENSORS 25

2.4. PHYSICAL EXERCISE PROTOCOL 26

2.5. SYSTEM SOFTWARE 31

2.6. PHYSICAL ACTIVITY ASSESSMENT OF THE STUDY POPULATION 35

2.7. ASSESSMENT OF THE USABILITY FOR THE SYSTEM 35

2.8. STATISTICAL ANALYSIS 37

3. RESULTS 38

4. DISCUSSION 42

5. CONCLUSION 48

REFERENCES 49

APPENDIX A: ETHICS COMMITTEE DECISION LETTER 56

APPENDIX B: SYSTEM SOFTWARE FOR EXERCISE SESSION WITH AUDIO BIOFEEDBACK 58

APPENDIX C: SYSTEM SOFTWARE FOR EXERCISE SESSION WITHOUT BIOFEEDBACK 68

LIST OF FIGURES

Figure 1.1. Knee joint anatomy 3

Figure 1.2. Long arm goniometer 6

Figure 1.3. Biofeedback methods 9

Figure 2.1. Knee motion-detecting auditory biofeedback generating system component diagram 15

Figure 2.2. Knee motion-detecting auditory biofeedback generating system circuit diagram 16

Figure 2.3. Seeduino XIAO 17

Figure 2.4. System circuit connection 18

Figure 2.5. 3D printed case 18

Figure 2.6. Top view of the 3D printed cover of the case 18

Figure 2.7. Side view of the 3D printed cover of the case 18

Figure 2.8. BNO055 MEMS sensor by Bosch 21

Figure 2.9. DFPlayer Mini pinout connections 23

Figure 2.10. Knee range of motion and sensor placement control 25

Figure 2.11. BNO055 placement case 26

Figure 2.12. Cover of the BNO055 placement case 26

Figure 2.13. Squat exercise movement pattern. (a) The starting position, (b) the descending phase of the squat. 28

Figure 2.14. Sit-to-stand exercise movement pattern. (a) The starting position, (b) Transfer of body's center of mass, (c) Stabilization. 29

Figure 2.15. Seated leg-flexion extension exercise movement pattern (a) The Starting position, (b) Knee straightened as fully as it can be... 30

Figure 2.16. Exercise protocol flowchart 31

Figure 2.17. Exercise software flowchart.. 32

Figure 3.1. Seated leg flexion-extension boxplot graph... 39

Figure 3.2. Sit to stand exercise boxplot graph... 40

Figure 3.3. Squat exercise boxplot graph 41

LIST OF TABLES

Table 1.1. Normative values of joint range of motion in the units of degrees by gender and age 3

Table 2.1. Inclusion and exclusion criteria for the study population 14

Table 2.2. Folder structure, files, and text read 24

Table 2.3. System Usability Scale Questionnaire adapted to Turkish 36

Table 2.4. Curved Grading Scale for the SUS 37

Table 3.1. SUS score assessed 38

Table 3.2. Seated leg flexion-extension range of motion sensed........ 39

Table 3.3. Range of motion sensed for sit-to-stand exercise 40

Table 3.4. Range of motion sensed for squat exercise 41

Table 3.5. Correlations 41

LIST OF SYMBOLS/ABBREVIATIONS

ACL	Anterior cruciate ligament
ADR	Address
CSV	Comma-separated value
DBS	Digital biofeedback system
IDE	Integrated development environment
IMU	Inertial measurement unit
IPAQ	Physical activity questionnaire-short
I2C	Inter-integrated circuit
LCL	Lateral collateral ligament
MEMS	Micro-electro-mechanical systems
MET	Metabolic equivalent task
MCL	Medial collateral ligament
PCL	Posterior cruciate ligament
PFJ	Patellofemoral joint
ROM	Range of motion
RX/TX	Transmit and receive
SD	Secure digital
SKÖ	System usability scale
STS	Sit to stand
SUS	System usability scale
TKA	Total knee arthroplasty
TFJ	Tibiofemoral joint
UART	Universal asynchronous receiver-transmitter
uMARS	Mobile application rating scale

1. INTRODUCTION

1.1. AIM OF THE STUDY

This thesis aims to improve the efficiency of knee-based exercises by quantifying the knee joint range of motion and giving audio feedback by playing predetermined dialogues with the use of an audio player module.

For that purpose, a system is designed to utilize three important functions during knee-based exercise: tracking and quantifying knee movement by using two micro-electro-mechanical orientation sensors, providing audio feedback regarding the movement quantified, and recording knee movement data for analysis in detecting any improvement during knee-based physical exercise with biofeedback. By using this designed system, the effectiveness of audio feedback is tested on sit-to-stand, squat, and seated leg flexion-extension physical exercises that are done by enrolled 15 volunteers. The gathered knee movement data are assessed using the Wilcoxon rank-sum test and volunteers assessed the designed system by System Usability Scale questionnaire.

1.2. ANATOMY AND MOVEMENT OF THE KNEE

The knee joint allows locomotion and stability through different terrains while reducing the forces that occur during activities [1]. It has a complex anatomy and kinematics (Figure 1.1). It is the combination of separate joints; the tibiofemoral joint (TFJ) and patellofemoral joint (PFJ). The femur articulates over the tibia and thus becomes TFJ and Patella articulates over the femur which makes PFJ. But the main complexity of the knee joint comes from the interaction between; the anatomy and geometry of the joint surfaces, active contraction of muscles and ligaments, menisci, and retinacula [1]. The full potential of a joint can move to a distance and direction is measured in the range of motion (ROM). Degree measurement is used to measure the amount of movement through a normal ROM [2]. During gait, the knee has the most frequent movement. TFJ rotates in a sagittal plane which is the motion of flexion and extension. This is the primary motion of the TFJ and therefore this motion makes it considered as a hinge joint in a simplified description. This flexion rotation in the sagittal plane can reach about 130 degrees' active flexion and up to 160 degrees in passive flexion.

Some individuals also seem to have hyperextension up to 5 degrees. But in detail, these rotation motions in the knee occur with coupled rotations in the coronal and transverse plane and which causes incongruency between the articulating surfaces [1]. Moreover, during the extension of the knee, PFJ has a complex three-dimensional motion across TFJ joint flexion in order minimal quadriceps contraction. In conclusion, the knee has three rotations: flexion and extension, external and internal rotation, varus and valgus angulation, and three translations: anterior and posterior glide, medial and lateral shift, compression, and distraction, in a total of 6 degrees of motion [3].

To guarantee knee joint stability during motion, support from soft tissues and muscle tensions are needed. Ligaments are elastic bands of tissues that connect bones and provides stability and strength to joints [4]. There are four ligaments in the knee: Anterior Cruciate Ligament (ACL), Posterior Cruciate Ligament (PCL) Lateral Collateral Ligament (LCL), and Medial Collateral Ligament (MCL). Cruciate ligaments (ACL and PCL) connect the femur and tibia and in this process, the ligaments cross each other. In flexion and extension motions, the anteroposterior rolling and sliding kinematics of the TFJ is controlled by ACL and PCL [5]. At zero degrees of flexion, the cruciate ligament’s function is to resists varus displacement. ACL resists the anterolateral displacement of the tibia on the femur. Without ACL hyperextension could not prevent hyperextension and PCL's primary function is to resist posterior tibial displacement [6]. Collateral ligaments (MCL and LCL), prevents lateral and medial movement and act to stabilize the hinge motion. MCL is found on the medial side of the joint and it is the main restraint to valgus angulation and internal tibial rotation. LCL is the main restrain to varus angulation [6].

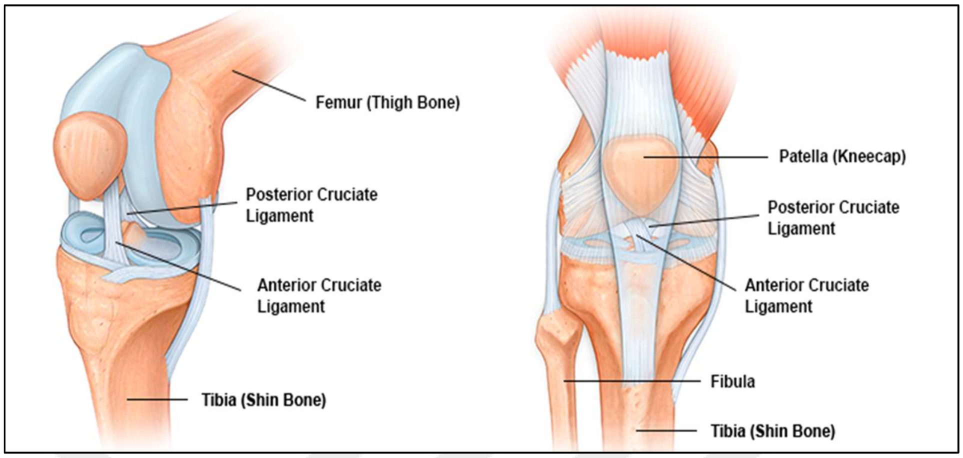


Figure 1.1. Knee joint anatomy [7]

The range of motion for knee flexion and extension differs for each individual. Besides, age and sex are the main factors that may influence the range of motion. The normal values for the motion by gender and age are as given in Table 2.1 [2].

Table 1.1. Normative values of joint range of motion in the units of degrees by gender and age [2]

Gender	Motion	Age 2-8	Age 9-19	Age 20-44	Age 45-69
Female	Flexion	152.6	142.3	141.9	137.8
	Extension	5.4	2.4	1.6	1.2
Male	Flexion	147.8	142.2	137.7	132.9
	Extension	1.6	1.8	1.0	0.5

1.3. KNEE INJURIES AND TREATMENT

Knee injury, arthritis, or mechanical problems can cause a decline in a person's quality of daily life. Most of these problems can show different symptoms depending on the cause of the problem. The symptoms may be knee pain, swelling, and stiffness, redness, and warmth on the touch, weakness or instability, popping or crunching noises, inability to fully straighten the knee [6]. For minor cases like, patellofemoral pain syndrome which is a common problem for the athletes that cause may be enough to treat it self-care. Physical therapy may also help or be the treatment. But in serious cases, surgery may be needed [6]. Medical conditions like Arthritis can occur in the joints and osteoarthritis is one of the most common types of arthritis that occur in the knee. Osteoarthritis occurs when cartilage in the knee deteriorates due to age and use and may cause severe damage to knee joints. The severity of the damage can be determined by orthopedic surgeons by assessing ROM and X-ray images of the knee. Exercise treatment can reduce pain and improve knee function which is the most preferred method of treatment used by the physiotherapist [8]. In the event of severe pain and loss of knee function due to osteoarthritis, knee replacement surgery also known as total knee arthroplasty may be performed to help relieve knee pain and restore its previous function [6]. In Turkey, from a prevalence study done in 2016, the Social Security Institution Medical Messenger records were scanned and in a total of 284,400 primaries and 9900 revision knee arthroplasty operations were applied between 2010 and 2014, and the numbers are kept on growing each year which shows the increasing need of surgery and physical therapy [9].

1.4. PHYSICAL EXERCISES FOR KNEE

Physical therapy knee exercises target to cure knee deficiencies that hinder knee functions after knee injury or surgery and also aimed to regain knee function. Rehabilitation can provide a reduction in complications such as pulmonary embolism and wound infection and it can reduce pain, stiffness, and swelling in the knee. Moreover, it may also provide regaining strength, flexibility, and ROM [10]. Depending on complications, patients usually receive supervised physical therapy two to three times a week for weeks or months. The type of exercise and the benefits vary depending on the complication. After surgery, exercises that increase circulation in the leg and feet are crucial due to the risk of blood clots. Early postoperative exercises will also help improving knee movement and increase muscle strength. Those exercises include: Quadriceps sets, straight leg raises, ankle pumps, knee straightening exercises, bed-supported knee bends, sitting supported knee bends. Sitting unsupported/supported knee bends [11]. Activities also aid in recovery after the surgery. Performing daily activities and walking short distances like around the hospital are beneficial early-stage activities that can be done. With progress over knee strength and flexibility acquired from such exercises and activities, more difficult activities like stair climbing and descending can be done. It is an important strengthening and endurance activity [11].

Even with all benefits of physical therapy exercises, non-adherence rates can reach up to 76 percent [10]. Non-adherence to physical exercise may cause unnecessary health provider visits, an increase in the risk of complications, and decreased quality of life. There are different factors of non-adherence. Four of these factors are individual barriers, financial barriers, family and work responsibilities, and pain. Lack of education about rehabilitation, poor communication with the patient, or lack of appreciation for rehabilitation are some of the individual barriers that cause non-adherence. Limited access to rehabilitation facilities and difficulties in managing payments are financial barriers that individuals face. Patients that have no financial barriers may also face difficulties at accessing rehabilitation, due to family or work responsibilities in daily life. Pain is another important factor that prevents the patient from doing rehabilitation [10]. For these barriers, remote rehabilitation using inexpensive portable devices can be a potential alternative method of solution.

1.5. ASSESSMENT OF KNEE MOTION DURING EXERCISES

Assessing knee motion during physical exercises provides optimized movements by minimizing the risk of injury while maximizing performance. Universal goniometers are considered the gold standard to measure joint angles (Figure 1.2) [12]. A goniometer is aligned on both sides of the joint and mobility can be read using its two movable arms; one of these arms has a circle with degrees of angle on it and the other arm is moved to measure the angle of the joint. Goniometers are separated into two variants: Long-arm (50 cm) and short-arm (30 cm) goniometers. Compared to long-arm goniometers, short-arm goniometers give less accurate measurements [12]. However, both goniometers give high inter and intra reliability, which suggests that using a single device, measurements between users and from the same user can be compared on a condition that minimum significant difference of the device is considered. If a joint angle measurement unit has a good inter- and intra-reader reliability and the minimum significant difference, it can be accepted as useful [13].

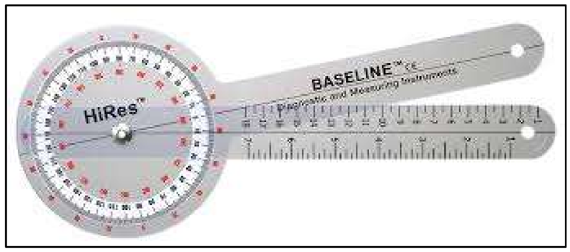


Figure 1.2. Long arm goniometer

In a systematic review, movement assessment methods for lower limb exercise are separated into four distinct methods: visual analysis from a qualified exercise professional; 3D motion capture; depth-camera-based systems; and self-assessment [12]. Each method has its advantages but also limitations. The visual assessment of ROM is performed under the supervision of qualified professionals like surgeons, athletic therapists, personal trainers, or physiotherapists. However, there are complications for both the supervisor and the patient. For supervisor; even though it is a quick and relatively easy method, visual assessment of human motion is considered not accurate amongst novices and experts due to presence of many constituent components that needs to be visually assessed which makes it difficult assessing simultaneously. For clients; lack of any supervisors and not being able to afford a supervisor due to financial barriers are two of the main complications [12]. For these reasons, people may prefer self-assessment but findings show that people are less accurate during self-evaluation compared to evaluating the performance of others and some evaluate themselves more positively or negatively than justified [14]. 3D motion capture systems and depth camera-based systems provide highly accurate and reliable kinematic data recordings of the human body which can be considered to be more efficient therapeutic decision making than the traditional assessment method. Optoelectronics is one of the commonly used sensors used in motion capture. It uses markers to obtain body segments and joints' position and orientation [15]. However, most of these systems are expensive and the application of skin-mounted markers may hinder normal movement which results in setbacks. Moreover, depending on the application, a space may be needed to work without a flaw. The presence of other people and equipment may cause a decrease in the accuracy of the system [12]. Expertise for using the motion capture systems and processing the collected data is also needed, which limits the usage of these systems beyond a research lab [12].

Smartphones have been increasingly used to estimate angles by using embedded accelerometer sensors. However, having so many applications that provide angle estimation creates a difficulty for comparing and testing the reliability of these systems. Some publications that compared the long-arm goniometer and smartphone app figure out that even some of the smartphone apps have higher accuracy, they are not advocated to use it for assessment in clinical usage due to limitations [13]. Having good reliability and low potential error in measurement does not enough for a measurement unit, it also needs to be user-friendly and should be quick to use for clinical usage. Software and hardware developments are also other limitations. Using different models of a smartphone leads to inherent error due to software and hardware difference [13].

Digital goniometers provide better accuracy and reliability compared to universal goniometers. HALO, a digital goniometer, is reported to achieve the best performance with high reliability both in knee and shoulder movement assessments [13,15]. The goniometer uses lasers, magnetic systems, and accelerometers, to guide alignment with anatomical landmarks, and it's one of a kind in commercially available systems [15]. However, limited availability and high cost are the setbacks for this system when compared to universal goniometers.

Inertial sensors are another type of device that is used to estimate the three-dimensional kinematics of a body segment. Inertial measurement units (IMU) have been commercially available and have been used in applications for vehicles but for more than a decade, it is available on almost all mobile devices [16]. Since they are considerably cheaper, easy to use and small in size, and portable, the interest in creating many applications for the automated assessment of lower limb exercises with wearable IMUs has been increased [13, 18]. In physical therapy, IMUs have been used to detect and measure the number of repetitions in a given exercise and to estimate ROM [19, 20]. It has been shown that IMU is an alternative method to a marker-based system as it is similarly effective in measuring joint angles [21, 22]. Different variants of IMU such as fiber optic gyroscope, ring laser gyroscope, micro-electro-mechanical systems exist.

Micro-Electro-Mechanical Systems (MEMS) is a technology used to create integrated devices that consist of a combination of mechanical and electrical components. In general, a MEMS unit is a silicon chip that includes mechanical microstructures, microsensors, microactuators, and microelectronics [22]. Compared to other types of gyroscopes, these systems provide better performance by being cheaper, smaller in size, less power consumption, and having multiple axes sensing digital sensors that make them more preferred in motion tracking to analog inertial sensors [16]. Different combinations of accelerometers, gyroscopes, magnetic sensors, and barometers can be used to create MEMS inertial motion sensors. Accelerometers mainly measure the force which occurs due to vibration or acceleration of motion. Gyroscopes can measure the orientation and angular velocity of an object. Magnetometers give a heading of an object based on the earth's magnetic field and barometers measure absolute and relative altitudes. While gyroscopes function autonomously and can track complex rotational motions in free space, accelerometers depend on gravity and magnetometers depend on the magnetic field.

By combining different MEMS subunit sensors in a single module and IMU is one of these modules that use the combination of motion sensors. Recognized modules for the purpose are 6-axis IMU (3-axis accelerometer, 3-axis gyroscope), 6-axis Static IMU (3-axis accelerometer, 3-axis magnetometer), 9-axis IMU (3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer). The data output by an IMU can be processed by a processor by using algorithms to calculate absolute orientation [23].

1.6. BIOFEEDBACK IN EXERCISES

Biofeedback is a self-regulation technique to voluntarily control the body processes of the individual [24]. The control is provided with the usage of the acquiring real-time information that can be referred to as augmented or extrinsic feedback which is not naturally available to the individual. The measured target biomedical variable is relayed to the individual as either direct feedback or transformed feedback (Figure 1.3). In direct feedback, the measured target biomedical variable is displayed as a numerical value on a screen. In transformed feedback, visual or auditory signals are triggered with the acquired biomedical variable from the individual [25]. These signals differ depending on the method used: haptic biofeedback gives vibrotactile signals to patients with stroke for postural control [26], audio biofeedback notifies the patient to perform the exercise correctly, a visual feedback system that provides motion tracking of the knee movement for physical rehabilitation of the knee [10] or combination of multiple feedback methods.

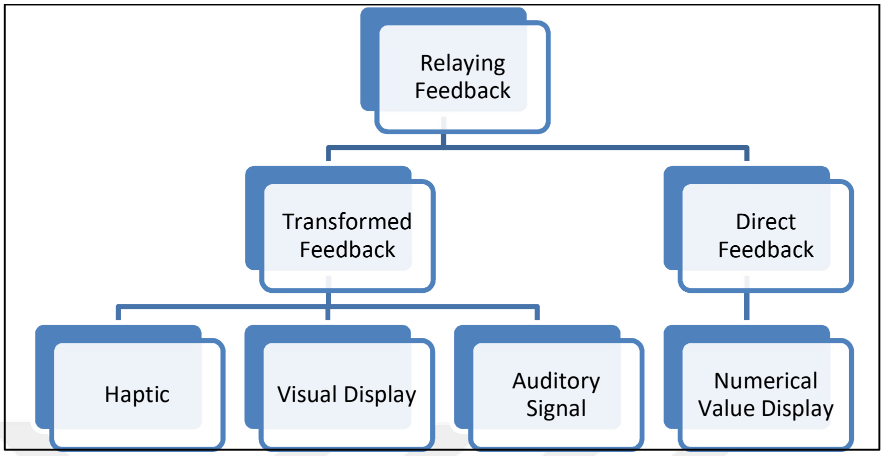


Figure 1.3. Biofeedback methods

Biofeedback can be classified in many different ways regarding the type of signal used. Biofeedback measurements used in physical rehabilitation are mainly categorized as physiological or biomechanical biofeedback. Physiological biofeedback is the signals acquired from the neuromuscular, cardiovascular, and respiratory systems of the patient's body. For biomechanical biofeedback, mainly, movement, postural control, and force produced by the body are measured [25]. To acquire biomechanical biofeedback, a system like electro goniometers, inertial measurement unit systems, camera-based motion capture systems can be used. Since the devices used to obtain biomechanical biofeedback can give different types of biomechanical feedback as output, biomechanical biofeedback can be considered to be more complex than physiological biofeedback.

Physical rehabilitation is one of the areas that biomechanical biofeedback can be used. Rehabilitation can be performed either in a medical center or at home as home-based physical rehabilitation. Mostly, biofeedback systems that are used in physical rehabilitation have the components: an input sensor to receive the feedback data acquired from the patient, a data processing system that processes the input data, and an output device to display the feedback data can be called digital biofeedback system [17]. With the addition of biofeedback, the patient's awareness of the exercise technique improves, and motor learning and engagement increase. It can provide objective measurements that can be given in physical rehabilitation in real-time or during exercise. Knee ROM is one of the objective measures that act as a rehabilitation goal, and with appropriate tools, data obtained during exercise can be used to monitor progress and even be used for telerehabilitation, allowing the physiotherapist to monitor progress remotely [18, 28, 29].

In the scoping Review of Louise Brennan, it has been stated that feedback consists of four main components: mode, content, frequency, and timing [17]. These components can be applied in multiple ways and almost every feedback design can be different from each other and theoretically, have different effects on the user. The first component, feedback mode, can mainly be audio, visual, or haptic. If multiple modes give the same variable at the same period, this mode is called a multi-model. The feedback can be given through these modes in either a direct (e.g. ROM) or indirect manner (e.g. abstract graphical display). The second component, time, is separated as concurrent (real-time or simultaneous) or as terminal (during or after exercise execution). The third component is frequency. The frequency of the feedback can be constant, fading, or reduced. The last component, the content of the feedback, may give the user the knowledge of the result or knowledge of the performance. Choosing the right combination of these components may result in the creation of a system that can positively affect physical rehabilitation, or the system created may be unnecessary or confusing for the user and may even hinder or reduce the benefits of physical rehabilitation. For this, the selection of DBS components is very important and, in this process, the decisions taken for the selection of the components should be discussed and the reason for the selection should be stated. Evaluating the feedback within the system can also be an alternative for providing an evidence-based rationale. Evaluating feedback components will provide the efficacy of the feedback and also justify its inclusion.

Biofeedback systems have great potential in unsupervised home rehabilitation. Exercise programs given for home rehabilitation plays an important role in patient's recovery. If done properly, exercise programs are essential for the patient to improve their condition. These programs mainly consist of targeted exercises which will increase strength, reduce pain and improve function activity. Targeted exercises are defined as; "specific rehabilitation movements, prescribes in terms of 'repetitions' and 'sets' which are repeated and progressed over time, to improve strength, ROM or function in a specific joint, muscle or group of muscles." [17]. Training that includes a great amount of repetitive movement can result in improved recovery and should be done regularly but this repetition without proper supervision or at home can cause uncertainty and loss of interest which will result in poor performance [17].

There are many examples of systems that use digital biofeedback in different health conditions [18, 30]. These conditions include, patients who had total knee arthroplasty (TKA), a major surgery, showed an improvement in their condition after exercising with biofeedback. Improvement of the patient's gait symmetry, reduction of pain, and increased physical activity proved a potential benefit of using biofeedback for TKA [29]. Using biofeedback during rehabilitation, patients and clinicians may have the benefit of further regulation over their physiology, and with this, it can have a potential therapeutic effect [30]. One method for regulation is to use orientation measurements acquired from the IMU as input for biofeedback systems. The system then may give direct feedback which displays the IMU data to the user via a screen or it can give transformed feedback such as auditory signals where the user receives a voice or sound which depends on the input signal that the system received [25]. However, it is not possible to decide on the most effective method without further study, as there are different types of biofeedback used with different devices and providing significant improvement [17]. Also, the infrequent use of digital biofeedback systems with targeted exercises in-home rehabilitation indicates that more studies are needed for such systems.

An important factor in choosing the type of biofeedback might be considering the acute phase of the injury. The acute phase of rehabilitation should begin as soon as possible and during acute phase rehabilitation, muscles and joints must be focused by doing a range of motion and muscle strengthening exercises to achieve the best possible functional outcome [31]. With the acute phase rehabilitation, motor activities recover better and affect the daily life of the patients positively. However, in the acute phase of rehabilitation, patients are often unable to continue watching their screens. Auditory feedback can be a useful tool when there are circumstances like in the acute phase, where patients will rely on auditory stimuli when they are not able to properly benefit from visual feedback [31]. Robotic systems in motor activity rehabilitation also have many advantages, but the need for customization and the possibility of high costs for patients to benefit from these systems reduce the likelihood of patients benefiting from robotic systems after discharge from the hospital. In motor activities rehabilitation, robotic systems also possess many advantages yet they may need to be customized and have high costs makes it less possible for some people. Audio feedback plays a great role in both these disadvantages. It is an inexpensive resource that requires minimum hardware requirements. It also can be customized depending on the user's needs and may even be used with other feedback devices.

Another important advantage of auditory feedback is that it can be used for home-based exercises. The patient’s recovery can be improved with physical exercises which consist of highly repetitive movements. These exercises require the active participation of the patient and also the motivation of the patient must be maintained during the physical exercise. After hospital discharge, the absence of any type of support from somebody during exercise may result in a decrease in motivation and the continuity of the exercise. It is known that auditory feedback during exercise brought motivation and there is evidence that presents an improved mood and performance, increase in engagement and learning during task-oriented applications [31–33].

The design of an audio feedback system is an important task. A poor design can cast down the patient’s morale and motivation rather than motivate them during physical therapy. Many conditions must be considered and a guideline should be followed when creating auditory feedback. The words or sounds used in the audio feedback are needed to be directly related to the experiences during the exercise. The sound of the feedback should not be confusing, otherwise, the user may disable the audio feedback. Avanzini et al. [31] made a comparative analysis by investigating all the papers referenced in review articles which include a robot-assisted system and auditory feedback to investigate the importance of rehabilitation systems. The comparative analysis resulted in separating auditory displays into four typologies. From most used to least, these typologies are Earcons, auditory icons, sonification, and synthetic speech. The earcon feedback is short pieces of music that characterize an event, the auditory icon feedback is made of everyday sounds mapped to computer events, the sonification consists of multidimensional datasets mapped into an acoustic domain and lastly, the synthetic speech is an artificially produced human voice.

1.7. AIM AND OBJECTIVES OF THE CURRENT THESIS WORK

The current objective is to explore improvements in the efficiency of knee-based physical exercises using audio biofeedback as biofeedback. These steps include planning the components of the biofeedback for exercise, planning and deciding hardware of the knee motion detecting and auditory biofeedback system, deciding exercise protocol and developing software for operating the system, collecting knee movement data during exercise protocol, and statistically analyze the data. Gathering and tracking the knee movement data during the exercise may provide information about the progress of the user and the influence of audio biofeedback that provides the knowledge of results during physical exercise will improve the efficiency.

The reason for choosing audio feedback is the advantages explained previously. The content of the feedback is knowledge of the result and has a fading frequency. Lastly, the feedback timing is terminal which means that the user or the patient receives the knowledge of the result during the physical exercise. There are not many reports about the use of a wearable system consisting of a combination of audio feedback and IMU for increasing the efficiency of lower extremity physical exercises.

2. MATERIALS & METHODS

2.1. STUDY POPULATION

The research for this thesis work has been approved by Yeditepe University Non-Interventional Clinical Ethics Committee (Approval ID: 202104017/7). Inclusion and exclusion criteria are as listed in Table 2.1. The volunteers who give consent for the experiment fill in the demographic information form. AB/BA cross-over study design is used to compare the physical exercise program with audio biofeedback (A) and the physical exercise program without any biofeedback (B). If the volunteer does the first exercise with audio biofeedback, the same exercise program is done without any biofeedback in the next week. To minimize the order effect, ten volunteers are randomly assigned to the exercise with biofeedback in the first week, and the other ten volunteers are assigned to exercise without biofeedback the first week. Each volunteer is briefed about the purpose, process, and inclusion criteria for the study.

Table 2.1. Inclusion and exclusion criteria for the study population

Inclusion Criteria	**Exclusion Criteria**
Must be an adult	Age below 18 or above 65
Body mass index below 30	Body mass index above 30
No previous surgery on the lower extremities	Any previous surgery on lower extremities
No discomfort/complaints in lower extremities	Any discomfort/complaints in lower extremities
No past or present pathology or symptoms in lower extremities	Any past or present pathology or symptoms in lower extremities

2.2. KNEE MOTION DETECTING AND AUDITORY BIOFEEDBACK GENERATING HARDWARE

The components of the knee motion detecting and auditory biofeedback generating hardware developed during this thesis work are presented in Figure 2.1. The hardware includes the given components: One Seeduino XIAO board (SEEED Technology CO., Ltd., Shenzhen, China) for controlling the operation of the components in the hardware, two BNO055 boards (Robert Bosch GmbH, Stuttgart, Germany) for quantification of knee movement, one micro secure digital module (Shenzhen LC technology Co. Ltd, Guangdong, China) for the storage of knee movement, and one mini audio player module (Zhiwei Robotics Corp., Shanghai, China). to generate audio feedback to the user. The hardware can be used with any external power supply which gives +5Vdc via a USB cable. The electronic circuit of the hardware is designed using Proteus Design Suite 8.10 (Labcenter Electronics Ltd., North Yorkshire, England) (see Figure 2.2).

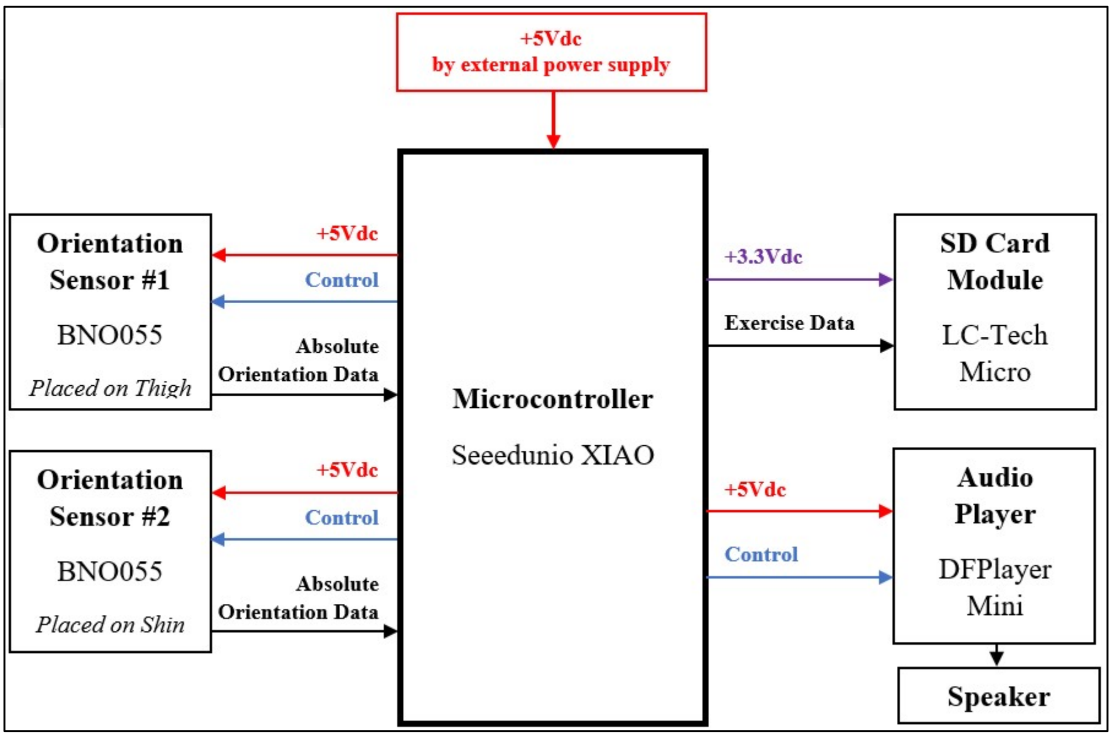


Figure 2.1. Knee motion-detecting auditory biofeedback generating system component diagram

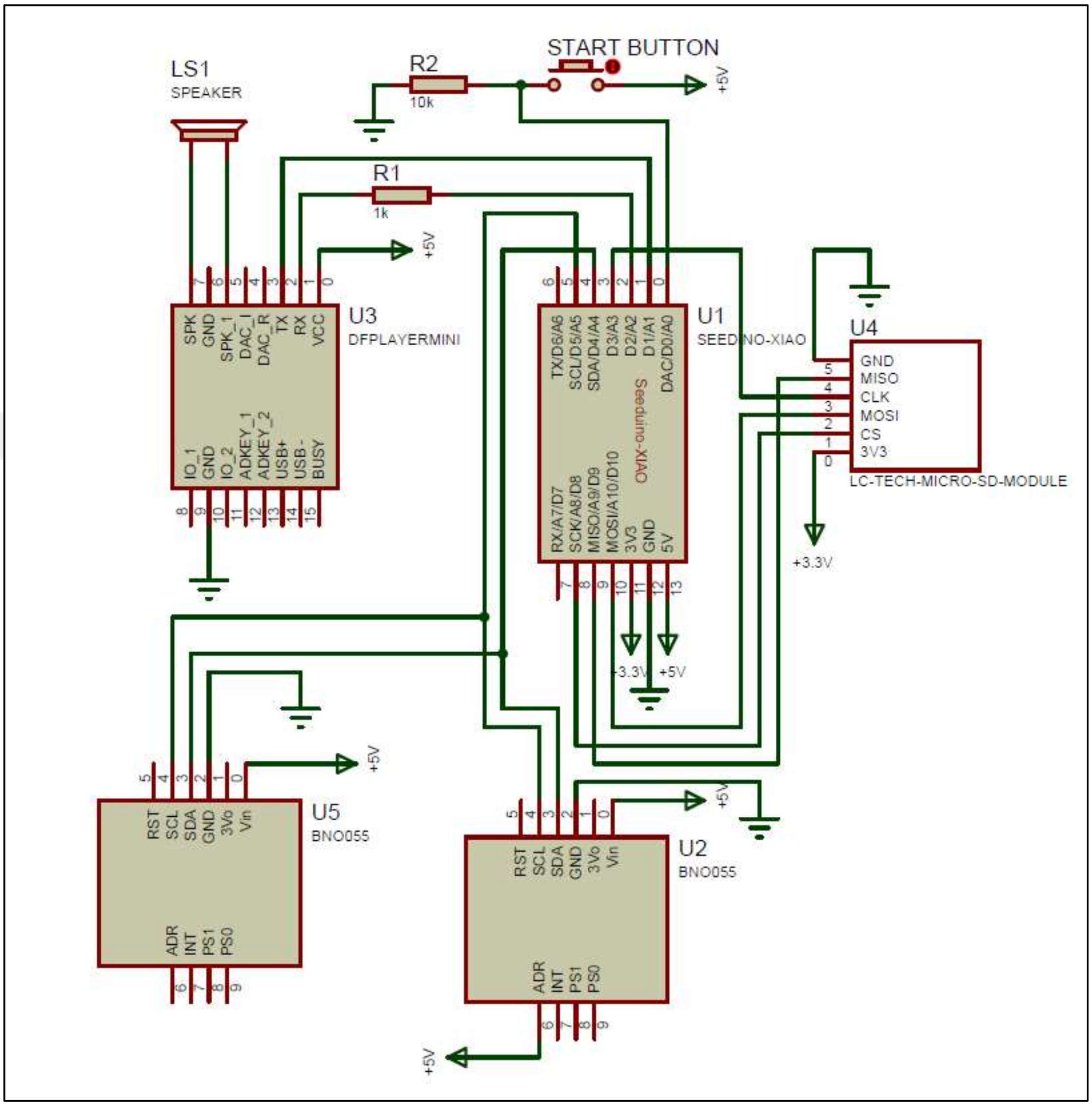


Figure 2.2. Knee motion-detecting auditory biofeedback generating system circuit diagram

Microcontrollers are controlling device that has memory and input/output(I/O) components internally and generally considered as the heart of the embedded systems. They are single integrated circuits that are used for implementing certain tasks. Microcontrollers can gather input, process this information, and based on the information it gathers, outputs an action. The Seeduino XIAO board (SEEED Technology CO., Ltd., Nanshan, Shenzhen, China) is used for storing and running the system software in the current work (Figure 2.3). The board is fully compatible with the Arduino software and Arduino shields. It is the smallest in the member of the Seeeduino family and is recommended for use in wearable devices. Even though it is small in size, it carries ATSAMD21G18A, a powerful, low-power, 32-bit, and 48 MHz microcontroller with 256 KB flash, and 32 KB static random access memory [34].

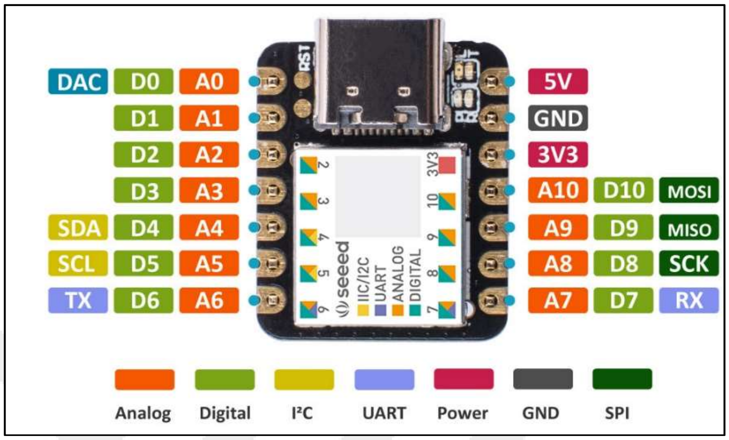


Figure 2.3. Seeduino XIAO

Compared to the previous board, Seeeduino provides creating a much smaller system for the thesis but it has fewer pins for analog or Digital Input/Output signals which may be a setback for some system designs. In addition to having fewer pins, in Arduino MKR1000, it is possible to add more serial interfaces for the SAMD microcontroller of the board, but in XIAO, this need for a second serial interface can be provided with a library called "SoftwareSerial" [35]. This library uses the built-in hardware support for serial communication allowing the chip to receive serial communication even while working on other tasks but as long as there is 64-byte room for serial buffer [35].

All components except the BNO055 were soldered and the circuit connection between the components was made on the protoboard (Figure 2.4). To connect the BNO055 sensors to the Seeeduino XIAO, the L-shaped male pin header was soldered to the protoboard. 70cm female-to-female Dupont jumper cables were used to connect pin headers and BNO055 sensors. A 3D case has been designed so that this protoboard circuit can be used as a wearable system. As illustrated in Figure 2.5, the holes were made on the designed case for attachable/removable parts of the system (BNO055 connection pins, SD card, USB port & push button). The loudspeaker required for audio feedback was attached to the 3D cover printed for the case.

Figure 2.4. System circuit connection

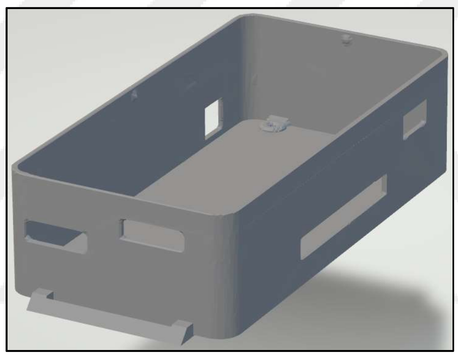


Figure 2.5. 3D printed case

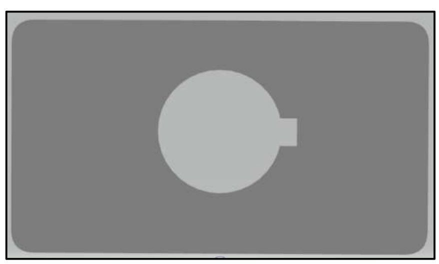


Figure 2.6. Top view of the 3D printed cover of the case

Figure 2.7. Side view of the 3D printed cover of the case

2.2.1. Quantification of Knee movement

The knee movement is quantified to track and record the progression of volunteers and provide feedback during an exercise. 3D space orientation measurement has been decided as the method for tracking and recording in this thesis. However, acquiring and reading 3D space orientation is a difficult task since the sensor data has to be acquired from accelerometer, gyroscope, and magnetometer. Generally, a sensor fusion algorithm blends these three sensor's data into a stable three-axis orientation output but getting this algorithm correctly is difficult to get.

Bosch is the first company that manages to get it in real-time and this data can also be used in quaternions, Euler angles, or vectors [36]. Euler angles are developed for describing and visualizing the orientation of a rigid body in 3D space by using a combination of three rotations about different axes. The product of three rotation matrices will give a general rotation matrix which is equivalent to Euler angles. However, its range of motion has been limited. In BNO055, yaw motion is in the range of 0°-360°, roll 0°-180° and pitch 0°-90°. The reason for these limitations is due to the gimbal lock that occurs when the pitch angles are near +/-90 degrees and prevents the system to work properly [37]. To solve this problem, quaternions should be used.

Quaternions are vectors in 4-dimensions; q_x, q_y, q_z components are imaginary numbers that represent the axis about which rotation occurs and w is a real number that represents the amount of rotation that occurs in that axis. By using these numbers, a matrix that represents all the rotations with no chance of gimbal lock can be built. Compared to rotation matrices, quaternions can be easily renormalized and by normalizing, angle and length distortions can be easily be avoided. These numerical inaccuracies occur due to floating-point computations which involve rotations. Quaternion is valued like in equation (3.1). The i, j, k values are the quaternion units, q_x, q_y, q_z and w are real numbers [37].

$$q = w + iq_x + jq_y + kq_z \tag{2.1}$$

In decomposing rotations, the Euler angles, yaw, pitch, and roll are obtained from the quaternion values detected by the sensors [38]. The roll angle output changed as the knee flexion-extension movement occurred in relation to the placement of the sensors. The roll angle output difference between the two sensors was used to monitor knee range of motion.

$$yaw = \arctan\left(2 * \frac{w*q_z+q_x*q_y}{1-2\left(q_y^2+q_z^2\right)}\right) \tag{2.2}$$

$$pitch = \arcsin(2 * (w * q_y - q_x * q_z)) \tag{2.3}$$

$$roll = \arctan\left(2 * \frac{w*q_x+q_y*q_z}{1-2\left(q_x^2+q_y^2\right)}\right) \tag{2.4}$$

The BNO055 sensor integrates a triaxial 14-bit accelerometer, 16-bit gyroscope, and geomagnetic sensor, and a 32-bit microcontroller running the BSX3.0 FusionLib software (Figure 2.8). The software combines the acquired measurements from the accelerometer, gyroscope, and geomagnetic sensor to a ready-to-used advanced 9-axis fusion solution which reduces the complexity for the user and provides a robust absolute orientation vector. Algorithms for offset calibration of each sensor, distortion-free, and refined orientation vectors provided by Kalman filter fusion are also included in this software [39].

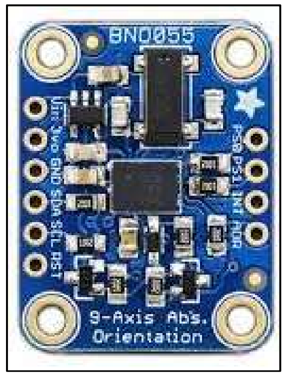


Figure 2.8. BNO055 MEMS sensor by Bosch [40]

BNO055's built-in algorithm provides various fused output data such as quaternion, Euler angles, rotation, and much more [41]. Adafruit provides an “Adafruit Unified Sensor” system that can be used to retrieve orientation in these data formats. Adafruit Unified Sensor Library provides a common interface and returns standard SI (International System) units. The library simplifies the retrieving quaternion and Euler data by just using the functions described inside [42]. Three functions were used to acquire quaternion values from the BNO055. The first function "sensors_event_t", is used to create an object to hold the Sensor's readings. The library's "get.event(&event)" function, reads a new set of values from BNO055 and places the readings to previously created object "event" placeholder [43]. By using the function "get.Quat”, Quaternion values in 3D-space were acquired [42]. After acquiring the quaternion values from each sensor, the values were normalized for accumulation of numerical round-off error. Finally, since the understanding of Euler angles is more intuitive and better for parsing rotations, Quaternion data is converted to Euler angles and the difference between roll angles in absolute orientation with respect to the placement of sensors is calculated to estimate knee range of motion. The whole procedure of acquiring the data were placed in a function and called whenever data was required from sensors.

In the thesis system, two BNO055 sensors are used. Both of these sensors are connected to the XIAO board. The second sensor is initialized on the same microcontroller with the same pin connection setup but in addition, the address (ADR) pin is connected to the +5Vdc output pin to change the I2C address of the sensor since having two sensors with the same I2C address may cause complications during data collection.

2.2.2. Storing of Knee Movement Data

Storing knee movement data during a physical exercise is very important because if there is an improvement in the conduct of physical exercise accompanied by biofeedback, evidence of this improvement must be provided. The system needs a larger memory to record the physical exercise progress data since Seeeduino XIAO has 256 KB flash memory and 32 KB SRAM which is not enough for data logging the whole exercise session and also separating each exercise's repetition would be cumbersome. SD memory cards are non-volatile memories and are one of many options that can be used for data storage. These cards may have three different sizes: the original size, mini size, and micro size. Their capacity ranges from 2 GB to 128 TB. In the current work, an 8 GB micro SD Card is used for storing each volunteers' exercise data.

To use a micro-SD card, a communication protocol is needed to communicate between the SD card and our system. By using an SD card module, the needed communication is provided for reading or writing data on an SD card. The LC Technology MicroSD card module [44] is used in this project. It uses a serial peripheral interface protocol for communication with the system. But there is a setback, it cannot use high-capacity memory cards; The module can work with SD cards with a maximum capacity of 16GB, but since the knee movement data will be stored as comma-separated value (CSV) format, it can hold a large number of files in the SD card (each set of one exercise can hold about 100 kilobytes, 8GB SD card can hold about 80,000 files).

2.2.3. Audio Player Module and Audio Files

DFPlayer Mini is a serial integrated MP3 player module that can be used either as a stand-alone module with an attached battery, speaker, and push buttons or with modules with RX/TX capabilities. It supports FAT16, FAT32 file systems and supports up to 32GB SD cards. It can store audio data in up to 100 folders, and each folder may store 1000 audio files. The audio formats supported by the module are MP3, WAV, and WMA. Specifying the music played and other functions are done through serial commands [45].

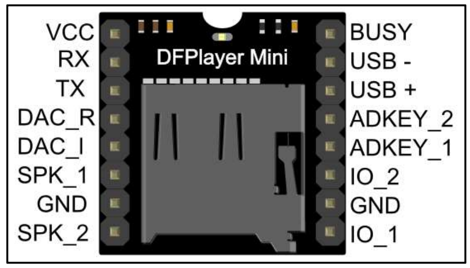


Figure 2.9. DFPlayer Mini pinout connections [45]

DFPlayer Mini module has been used in different projects as audio feedback. Two of these projects are smart guide extensions for the blind cane which gives audio feedback for blind or visually impaired users in daily life [46], a user-friendly cost-effective learning aid design for visually impaired students in India [47]. In the current work, the module is used to give audio feedback to the user during a physical exercise. Many audio feedbacks are created by speaking and recording predetermined dialogues and specific phrases. Audio recordings are created using the "Windows Voice Recorder" application, but the files created in this application are in m4a format which is not suitable for the MP3 module. Audio recordings in m4a are then converted and edited for effective use [48]. In the editing process, the unnecessary parts in the recordings such as background noise are trimmed. After editing, depending on the purpose of the audio files (telling exercise set/repetition, informing), they are stored in different folders inside the DFPlayer Mini's SD card. The audio files give audio feedback to the user by announcing pre-recorded dialogues. These dialogues include, beginning and end of the set/exercise, the ROM achieved, and repetition count during the exercise (see Table 2.2.)

Table 2.2. Folder structure, files, and text read

Folder Name	**Files stored in the folder**	**Files in the Folder**	**Pre-recorded Dialogue**
01	Audio files about setup process and informing the volunteer about which exercise is about to begin/end	002.mp3 003.mp3 004.mp3 005.mp3 006.mp3 008.mp3 009.mp3 011.mp3 012.mp3 013.mp3 066.mp3	“Sensor could not be found please check sensor connection” “First sensor detected please get ready for sensor calibration” “Second sensor detected please get ready for sensor calibration” “Calibration completed successfully” “Please press the button when ready” “Exercise is completed. Please press the button for new exercise when you are ready” “Today’s exercise is completed, congratulations” “Leg extension exercise has started” “Sit to stand exercise has started” “Squat exercise has started” “Greetings”
02	Audio files that announce repetition number	001.mp3 002.mp3 003.mp3 004.mp3 005.mp3 006.mp3 007.mp3 008.mp3 009.mp3 010.mp3 011.mp3 012.mp3 013.mp3 014.mp3 015.mp3	“One” “Two” “Three” “Four” “Five” “Six” “Seven” “Eight” “Nine” “Ten” “Eleven” “Twelve” “Thirteen” “Fourteen” “Fifteen”
03	Audio files that announce exercise ROM value	001.mp3 002.mp3 … 101.mp3	The ROM value is one less than the relevant filename (e.g. file "003.mp3" plays the ROM value “Two”).
04	Audio files that announce which set finished	002.mp3 003.mp3	“End of the first exercise set” “End of the second exercise set”

2.3. PLACEMENTS OF THE SENSORS

Two BNO055 sensors have been used in the hardware developed: one is placed on the lateral side of the thigh and the other one on the lateral side of the shinbone (see Figure 2.10). The sensor positions are checked using a long-arm goniometer after the placement of the sensors. To place the sensors on the user's leg correctly and to prevent any unwanted movement, the 3D printed case and cover case cover designs shown in Figures 2.11 and 2.12 are done. After the sensor is placed in the case, it is sewn to the modular leg straps that are attached to the wearer's leg.

Figure 2.10. Knee range of motion and sensor placement control

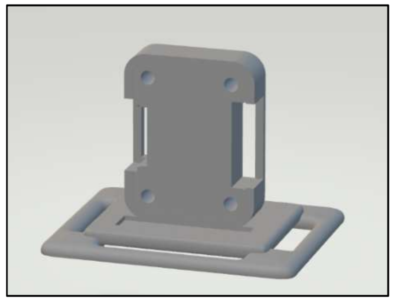


Figure 2.11. BNO055 placement case

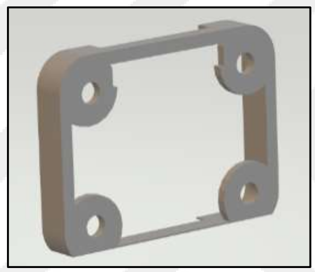
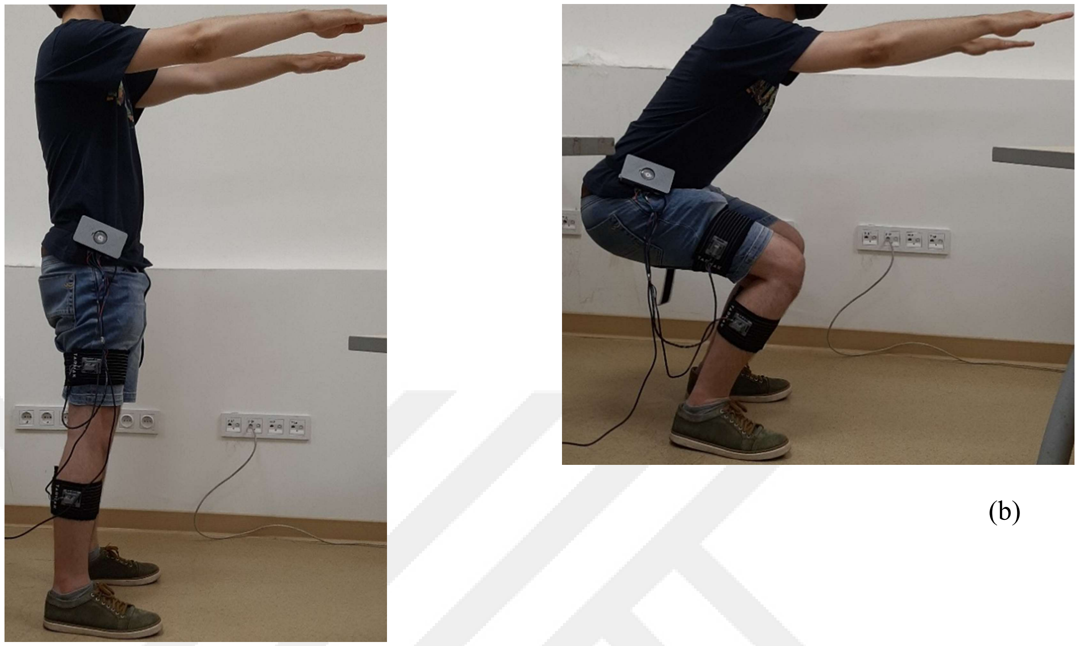


Figure 2.12. Cover of the BNO055 placement case

2.4. PHYSICAL EXERCISE PROTOCOL

Patients who undergo knee joint replacement surgery are encouraged to do knee-focused exercises to restore the normal range of motion for the knee. To analyze the improvements in the knee, three different exercises have been considered in this thesis work. In a systematic review, the most commonly investigated exercises are lying leg raise, sit-to-stand, and squat [12]. However, lying leg raise exercise is mostly used for helping low back pain. Instead, seated leg flexion-extension is picked which seems to be one of the most investigated knee-based exercises [12]. In daily life, essential activities like sitting and lifting require a squat movement pattern. The squat is an important exercise that reduces the risk of injuring the knee [49]. It strengthens the muscles in the lower limb and increases the resistance to have a medial or lateral displacement of the knee. However, compared to other exercises, squatting is also identified as a strength exercise that has a higher risk of injury for the lower limbs and the trunk [50]. There are guidelines for executing squat which instructs about the foot stance and placement angle, knee motion, hip depth, and extra load. Despite that, squatting techniques vary, almost all squat variations are done to support progressive physical attribute improvement and decrease the risk of training-induced injury. Due to these different techniques, there are different opinions about the most effective squatting technique among therapists, coaches, and experts [49].

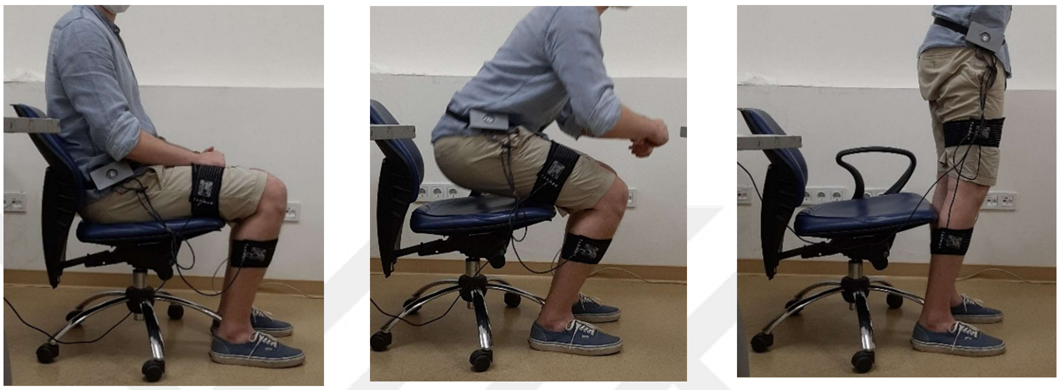
Squat motion often begins with the standing position with the feet flat on the floor, the knees and hips are in the neutral position, and the spine in the upright position. The second phase of squat is the descent. In this phase, ankles, knees, and hips flex. This phase continues until the top of the thigh is at least parallel with the ground and the hip joint is slightly below the knee joint. The third phase, ascent, is achieved by triple extending the hips, knees, and ankles until returning to the original starting position [50]. In the exercise protocol, volunteers execute the three-phase squat movement. This movement is done in 10 repetitions over 3 times per session and the knee rotation angle is tracked and recorded by the system developed.



(a) (b)

Figure 2.13. Squat exercise movement pattern. (a) The starting position, (b) the descending phase of the squat.

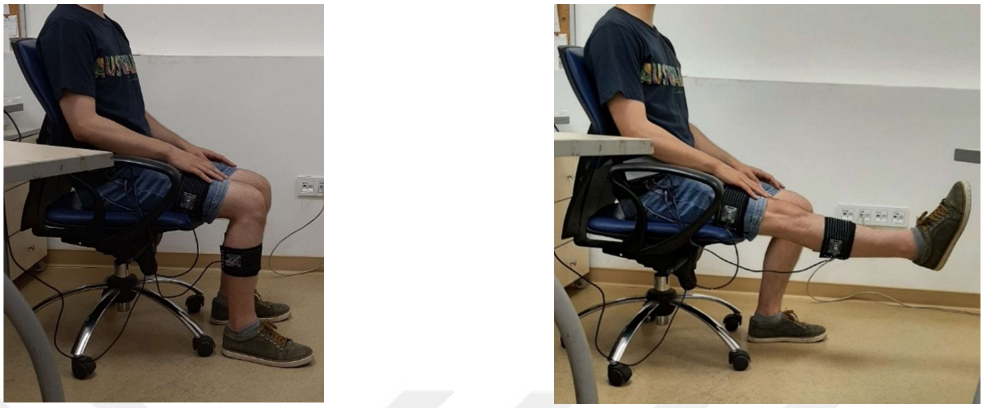
Sit to stand (STS) exercise is defined as a transitional movement from sitting to upright standing posture. It is a very common and crucial task which is rising to stand position from sitting and adults who have no disability perform this task about 60 times per day. In clinical practice, the ability to STS is evaluated through performance-based tests done by counting the number of repetitions in a predetermined duration or by reporting the time elapsed in doing five or 10 repetitions [51]. STS is a transitional movement that requires horizontal and vertical displacement of the whole body's center of mass. The body's center of mass movement is done from a stable to a less stable position overextended lower extremities. This transfer of the body's center of mass has been divided into phases. The name of the main three phases is Flexion Momentum (Phase 1), Momentum Transfer (Phase 2), and Extension (Phase 3) [52]. In some articles, there is also a 4th phase that is difficult to identify according to some authors: Stabilization (Phase 4). The first phase begins when initial anterior movement occurs and ends when the buttocks leave the base of support. The momentum Transfer phase lasts from set-off to maximum ankle dorsiflexion. The third phase begins from maximum ankle dorsiflexion and lasts until the hips are straight [51]. In the current thesis work, the volunteers execute four-phase STS movement in 10 repetitions over three times per session (During exercise, the knee rotation angle is tracked and recorded by the system developed).



(a) (b) (c)

Figure 2.14. Sit-to-stand exercise movement pattern. (a) The starting position, (b) Transfer of body's center of mass, (c) Stabilization.

Active and passive stretching is one of the recommended exercises for restoring knee joint range of motion while avoiding long-term complications. In the first three weeks after the surgery, it is crucial to prevent any scar tissue within the knee joint by doing this exercise. To do this exercise, the knee is bent at a right angle (90 degrees flexion) while sitting on a chair or bed and after that, the operative knee should be straightened as fully as it can be and also should be held in that position for few seconds. This exercise is repeated in 3 sets of 10-15 repetitions and it is done 3 to 5 times per day [53]. In the thesis, the same exercise procedure is followed, each volunteer does 10 repetitions over 3 times per session and his/her knee rotation angles are tracked and recorded using the system prototype.



(a) (b)

Figure 2.15. Seated leg-flexion extension exercise movement pattern (a) The Starting position, (b) Knee straightened as fully as it can be

All physical exercises were carried out at the Biomedical Instrumentation Lab of the Biomedical Engineering Department, Yeditepe University. During exercise sessions, volunteers were supervised. The two orientation sensors were placed in the lateral side of the lower extremity: one sensor was attached to the thigh and the other one to the shin, and the system was placed on the waist with a strap. When the placement of both sensors was accomplished, outputs received from both sensors were inspected to check the positioning and calibration for the sensors. At the beginning of sessions, the volunteers were informed on how to perform the exercise and how to correct any errors experienced. When the system initialization and sensor calibration were accomplished, the volunteers were informed by the system with a pre-recorded dialogue. Depending on the session (with/without feedback), the volunteer received audible feedback announcing which exercise was started, as well as what repetition was finished. There was a 15-seconds break between each repetition and a 1-minute break at the end of each exercise. Sensor connections were checked for slippage at each interruption. If any slippage was noticed during the exercise, the recording of that repetition was noted and excluded from the analysis. At the end of each break, the volunteer pressed the “start” button again and started the next repetition or a new exercise depending on the number of repetitions completed. At the end of each session, the volunteer's knee motion data were transferred from the SD card to the computer. The whole process performed was as illustrated in Figure 2.16.

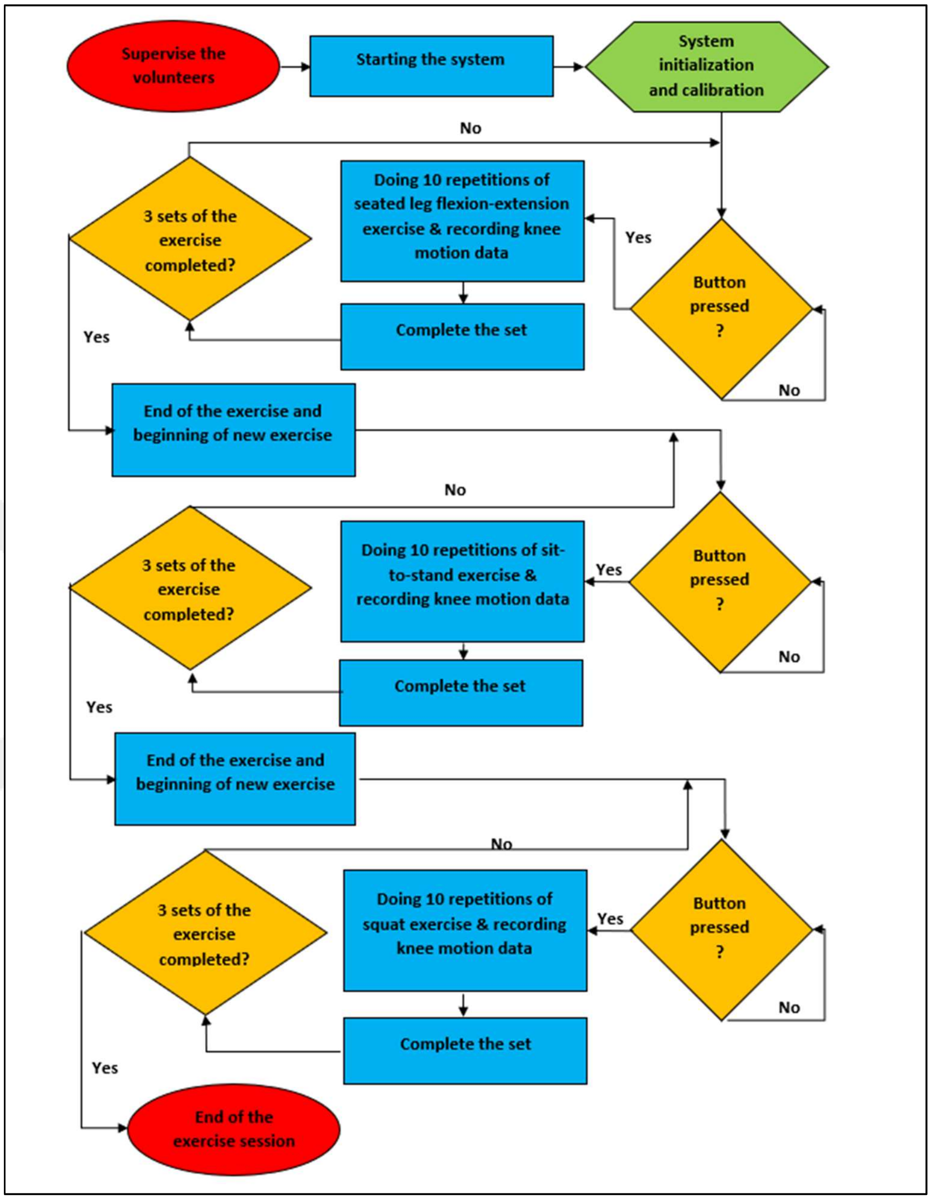


Figure 2.16. Exercise protocol flowchart

2.5. SYSTEM SOFTWARE

The system software has been developed using Arduino IDE (Integrated Development Environment). The software consists of two main parts: the system setup phase which is a long function where all component connections are checked and calibrations are performed, and the exercise phase which consists of series of functions that operate the system. The processes are as illustrated in Figure 2.17.

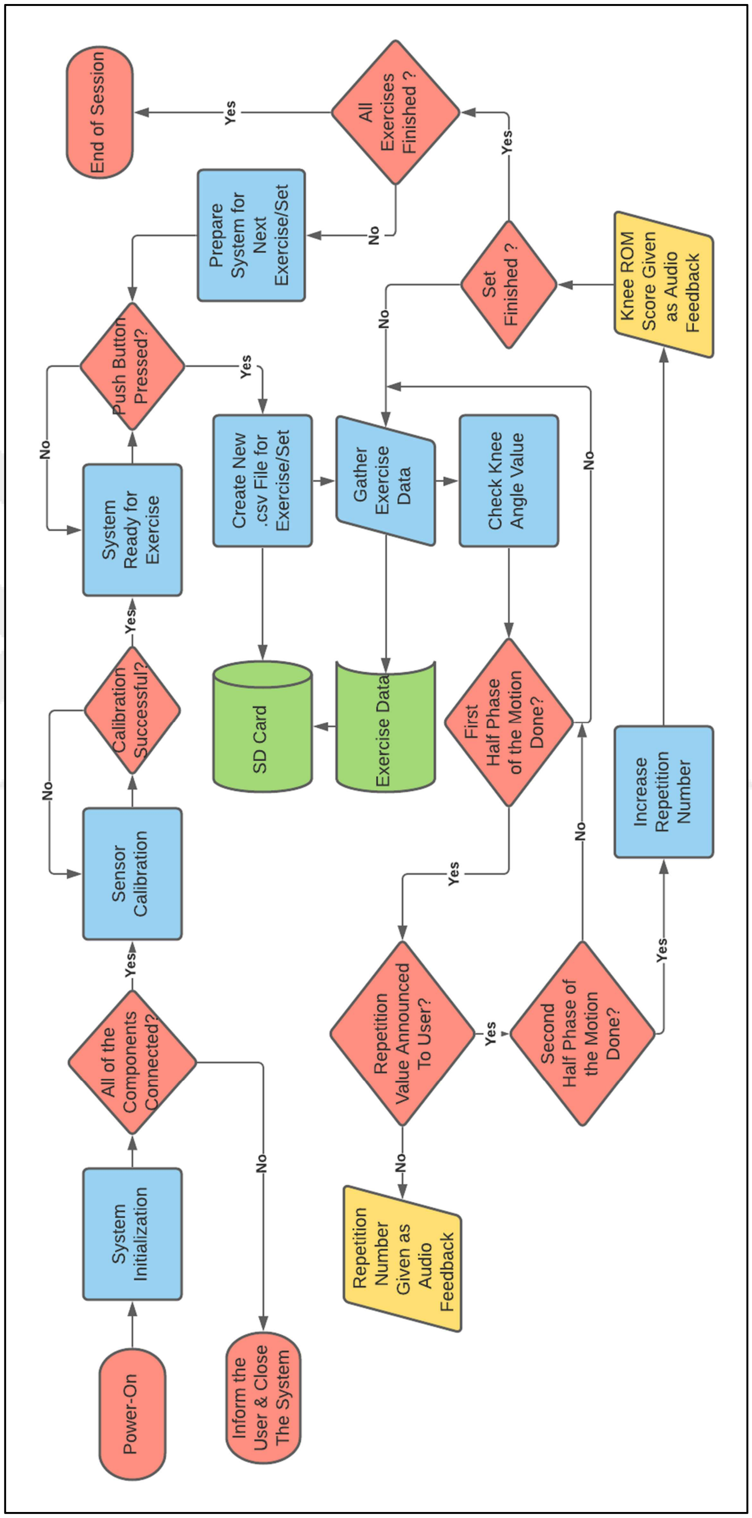


Figure 2.17. Exercise software flowchart

Before starting the exercise session, the connections of all system components (audio player, both orientation sensors, and data storage module) are checked in the setup function of the software. After the component connection check is completed and both sensors are successfully calibrated, the system notifies the user that it is ready to handle an exercise session. If any problem occurs during this setup process, depending on the problem, the system notifies the user by playing the pre-made audio recording reporting the problem, and then the system stops progressing to resolve the issue. After the setup phase, the exercise phase consists of three main tasks. For each exercise, a dedication function is developed. For quantification of knee movement, the functions that have been mentioned in 3.2.1. are used. The output given from the knee quantification function is used as an input value for all three exercise functions. Depending on the session (exercise with/without feedback), the commands for playing the decided audio files (announcing the start/end of the exercise/set, the angle done in the repetition, repetition number) are included in the exercise functions. Details for each exercise function are given in the following paragraphs. Before the beginning of each session/exercise, the software commands the data storage module to create a new CSV file with a different name in the SD card of the data storage module and during each session/exercise, the software records the knee motion data into the created CSV file.

With the knowledge acquired from the articles that provide the phases of the squat exercise and how to execute the exercise correctly, the key points for designing the squat exercise software design are decided [49,50]. In the squat, to achieve the second phase of the descent (squatting motion), and to have a standard angle value for the knee, 90 degrees is taken as the desired angle value. The system has the algorithm to track the range of motion of the knee during squat motion. The phases of squatting exercise are taken as a model for the squat exercise algorithm. The exercise only begins when the individual is ready and the "Start button" on the system is pressed. The button is pressed when the individual is the position in the first phase and announces the beginning of the exercise. During the exercise, the individual's ROM is recorded without any interruption. When the individual descends and flexion of the knee has more than the threshold knee angle (i.e., 60 degrees), the system recognizes that the decided threshold level for the second phase of the squat motion is completed and it informs the volunteer about the exercise's repetition count as audio feedback. After the feedback, when the volunteer believes that the squatting motion is completed, the ascending motion begins to the original position which is an extension of the knee to zero degrees. Once the certain threshold range of knee angle (<5 degrees) is achieved for the ascending, the system gives the individual's recorded knee angle of the current repetition, which is desired to be as close as possible to 90 degrees. This knee joint angle recording is done by a simple method: creating a float variable (a number that has a decimal place) for knee joint angle and having the initial value as zero in the beginning and comparing each recorded value from this variable. If the recorded angle value is bigger than the current variable value, then the variable value is equal to this new recorded angle. Once the final phase (ascending) finishes, the variable value is given as audio feedback, recorded in the set's output array, and then set to zero for the next repetition.

With the knowledge acquired from the articles that provide the phases of the STS exercise and how to execute the exercise correctly, the key points for STS exercise software design are decided [52, 53]. The key points in the system design are the maximum range of motion and the repetition number. For the current thesis work, an exercise has been made in three sets with ten repetitions. After pressing the "Start" button, the volunteer begins an exercise. Each time the volunteer stands up, the system gives the current repetition number as audio feedback and after sitting down for the next repetition, the system gives information about the knee joint angle during the stabilization phase (Phase 4). Just like in squat, each knee joint angle value is recorded in 10ms intervals and unlike from the squat, instead of maximum knee angle, the minimum knee angle values were announced to volunteer and recorded.

With the knowledge acquired from the article [53], the key points for the knee extension exercise software design are conducted. The exercise is performed in three sets each repeated 10 times. ROM is also crucial for tracking progress and during the exercise, the knee should be extended as much as possible for acquiring a precise result. Key points in the system design are the ROM and the repetition. First, set number and each set's repetition were decided, just like the other two exercises. After pressing the button, the volunteer begins the exercise, each time the volunteer extends the knee, the system gives the current repetition as audio feedback and after flexing the knee to the original starting position for the next repetition, the system gives information about the knee joint angle which are done during flexion phase. each knee angle value is recorded and just like in STS, the minimum knee angle values are announced to volunteer and recorded.

For the thesis experiment, two separate codes were used for AB/BA crossover design: One for exercise sessions with biofeedback and the other without any biofeedback. The codes were almost identical, only in the latter, any commands that give biofeedback were commented out which means those lines were not called while using that code. Depending on the volunteer's session, the respective code was compiled in XIAO. Both codes were given in the appendix section.

2.6. PHYSICAL ACTIVITY ASSESSMENT OF THE STUDY POPULATION

Before beginning an exercise session, each volunteer fills out a physical activity questionnaire-short (IPAQ) form designed for population surveillance of physical activity among adults [54]. There are seven questions on three variants of activity namely walking, moderate-intensity activities, and vigorous-intensity activities in the last seven days. The specific scoring for these exercises is reported as a continuous measure in the metabolic equivalent task (MET) or categories. MET minutes represent the amount of energy expended out of physical activity in a week. IPAQ scoring is separated into three levels, low activity level (MET score <599), moderate activity level (MET score between 600 and 2999), and high activity level (MET score >2999)

2.7. ASSESSMENT OF THE USABILITY FOR THE SYSTEM

To evaluate the usability of the system, the System Usability Scale (SUS) developed by Brooke in 1986 is used. The scale consists of a 10-item questionnaire with five responses for each question ranging from “Strongly agree” to “disagree” and can be used on small sample sizes reliably [55]. It is adapted into Turkish under the name of “Sistem Kullanılabilirlik Ölçeği” (SKÖ). In the internal reliability analysis, SKÖ shows good internal reliability (Cronbach Alpha value of 0.78), and the usability and learnable factors also have good results (Cronbach's alpha values of 0.79 and 0.60, respectively)[56]. In this thesis work, the Turkish version of SUS was used given in Table 2.3. After completing each session, the volunteers answered the SUS questionnaire.

Table 2.3. System Usability Scale Questionnaire adapted to Turkish [56]

Sistem Kullanılabilirlik Ölçeği *System Usability Scale*	**1** **Hiç katılmıyorum** *Strongly Disagree*	**2**	**3**	**4**	**5** **Tamamen katılıyorum** *Strongly Agree*
1. Bu sistemi sıklıkla kullanmak isteyeceğimi düşünüyorum *I think that I would like to use this system frequently*					
2. Bu sistemi gereksiz bir şekilde karmaşık buldum. *I found the system unnecessarily complex.*					
3. Bu sistemin kullanımının kolay olduğunu düşündüm. *I thought the system was easy to use.*					
4. Bu sistemi kullanabilmek için daha teknik bir kişinin desteğine ihtiyaç duyacağımı düşünüyorum. *I think that I would need the support of a technical person to be able to use this system.*					
5. Bu sistemdeki çeşitli fonksiyonları iyi entegre edilmiş buldum. *I found the various functions in this system were well integrated.*					
6. Bu sistemdeki çok fazla tutarsızlık olduğunu düşündüm. *I thought there was too much inconsistency in this system*					
7. Birçok insanın bu sistemi kullanmayı çok çabuk öğreneceğini sanıyorum. *I would imagine that most people would learn to use this system very quickly.*					
8. Bu sistemin kullanımını çok elverişsiz buldum. *I found the system very cumbersome/awkward to use.*					
9. Bu sistemi kullanırken kendimden çok emin hissettim. *I felt very confident using the system.*					
10. Bu sistemde bir şeyler yapabilmek için öncelikle birçok şeyi öğrenmem gerekti. *I needed to learn a lot of things before I could get going with this system.*					

The SUS score is calculated in two steps. Firstly, the sum of the responses to odd-numbered questions is calculated and five is subtracted from the total sum. Secondly, the sum of the responses to even-numbered questions is calculated and then subtracted from 25, The results are then added together and then multiplied by 2.5 to obtain a SUS score. The score obtained is used for grading the usability of the system considering the scores and grades listed in Table 2.4 [57].

Table 2.4. Curved Grading Scale for the SUS [57].

GRADE	SUS SCORE	PERCENTILE RANGE
A+	84.1	96 - 100
A	80.8 - 84.0	90 - 95
A-	78.9 - 80.7	85 - 89
B+	77.2 – 78.8	80 - 84
B	74.1 – 77.1	70 - 79
B-	72.6 – 74.0	65 – 69
C+	71.1 – 72.5	60 – 64
C	65.0 – 71.0	41 – 59
C-	62.7 – 64.9	35 – 40
D	51.7 – 62.6	15 – 34
F	0 – 51.6	0 - 14

2.8. STATISTICAL ANALYSIS

The differences between knee-based physical exercises performed with and without biofeedback were analyzed during statistical analysis. Wilcoxon Rank-Sum tests were used to determine the significant differences between each exercise type. Spearman's correlation test was used to measure the strength and direction of association between two ranked variables. Kolmogorov-Smirnov test was used for examining whether the data were distributed normally. The two-way hypothesis was considered. The null hypothesis, H0, was postulated as "there is no significant difference in knee joint angles and exercise repetitions in knee physical exercises with and without biofeedback, and similar exercise efficiency was achieved". The alternative hypothesis, H1, was postulated as "there are significant differences in knee joint angles and exercise repetitions in knee physical exercises with and without biofeedback, and biofeedback increases exercise efficiency by providing targeted angle values". During the analyses, a significance value of 0.05 was considered. All statistical analyses were performed using IBM SPSS Statistics 26 software (IBM Corp., Armonk, NY, USA).

3. RESULTS

Among the twenty volunteers who entered the study, only fifteen volunteers could manage to complete the work (8 volunteers in group B, and 7 volunteers in group A). Five volunteers are dropped due to not attending the physical exercises completely. Each volunteer takes two exercise sessions, one of these sessions is done with biofeedback and the other was done without biofeedback. The data for each exercise consists of ROM values acquired from 10 repetitions in three sets (a total of 30 knee ROM data is captured for each volunteer). All exercise session data are stored inside personal folders separately. The average score for the SUS test are respectively 83.0 (B+) and 72.2 (C+) however the difference is not significantly different (*P*= 0.14) (Table 3.1).

Table 3.1. SUS score assessed

	Mean ± SD	**Min - Max**	**Median**	***P***
Without feedback	72.2 ± 15.6	50.0 - 92.5	65.0	0.14
With feedback	83.0 ± 11.7	52.5 - 100.0	87.5	

In the seated flexion/extension exercise, the addition of audio feedback was not created a statistically significant difference (Table 3.2). The boxplot of seated leg flexion-extension shows that there is little difference between leg flexion exercise with biofeedback and without biofeedback (Figure 3.1).

Table 3.2. Seated leg flexion-extension range of motion sensed

Leg Flexion Exercise	Mean ± SD	Min - Max	Median	*P*
Without feedback	0.67 ± 1.84	0.00 - 27.73	0.10	0.15
With feedback	0.46 ± 0.90	0.00 - 5.32	0.08	

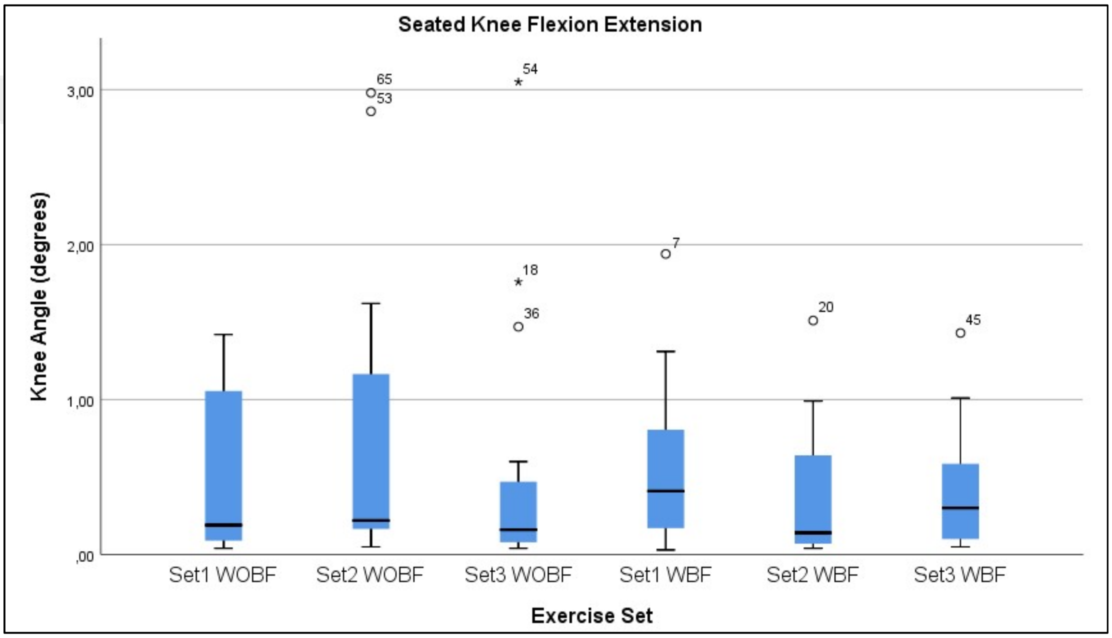


Figure 3.1. Seated leg flexion-extension boxplot graph

In the sit-to-stand exercise, the exercise data with biofeedback is less dispersed compared to sit-to-stand exercise data without biofeedback. The addition of audio feedback made a statistically significant difference (Table 3.3). This difference can be seen in the sit-to-stand exercise boxplot (Figure 3.2).

Table 3.3. Range of motion sensed for sit-to-stand exercise

Sit to Stand Exercise	Mean ± SD	Min - Max	Median	*P*
Without feedback	0.53 ± 1.88	0.00 - 34.97	0.06	0.01
With feedback	0.39 ± 0.97	0.00 - 6.18	0.05	

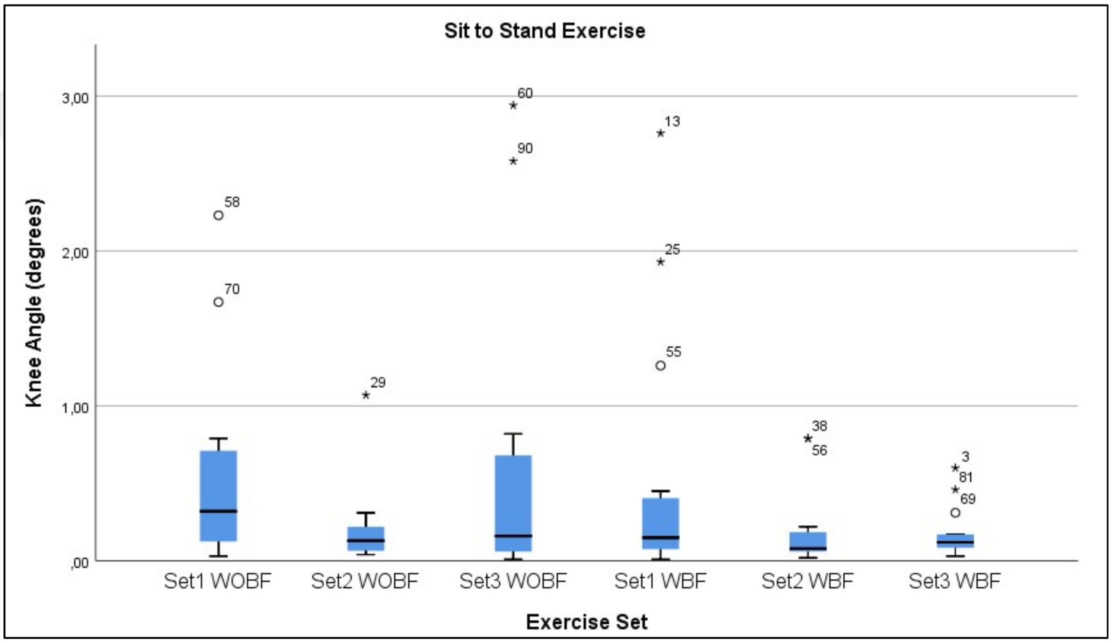


Figure 3.2. Sit to stand exercise boxplot graph

In the squat exercise, the determined knee angle value during squat motion is 90 degrees. Each volunteer focus on achieving to determined knee angle value (90 degrees) during the squat exercise. The exercise data with feedback is less dispersed compared to sit-to-stand exercise data without feedback. The addition of audio feedback made a statistically significant difference (Table 3.4). This difference can be seen in the squat exercise boxplot (Figure 3.3).

Table 3.4. Range of motion sensed for squat exercise

Squat Exercise	Mean ± SD	Min - Max	Median	*P*
Without feedback	94.20 ± 11.22	60.32 – 112.90	95.56	< 0.001
With feedback	89.74 ± 5.54	64.08 – 113.92	89.90	

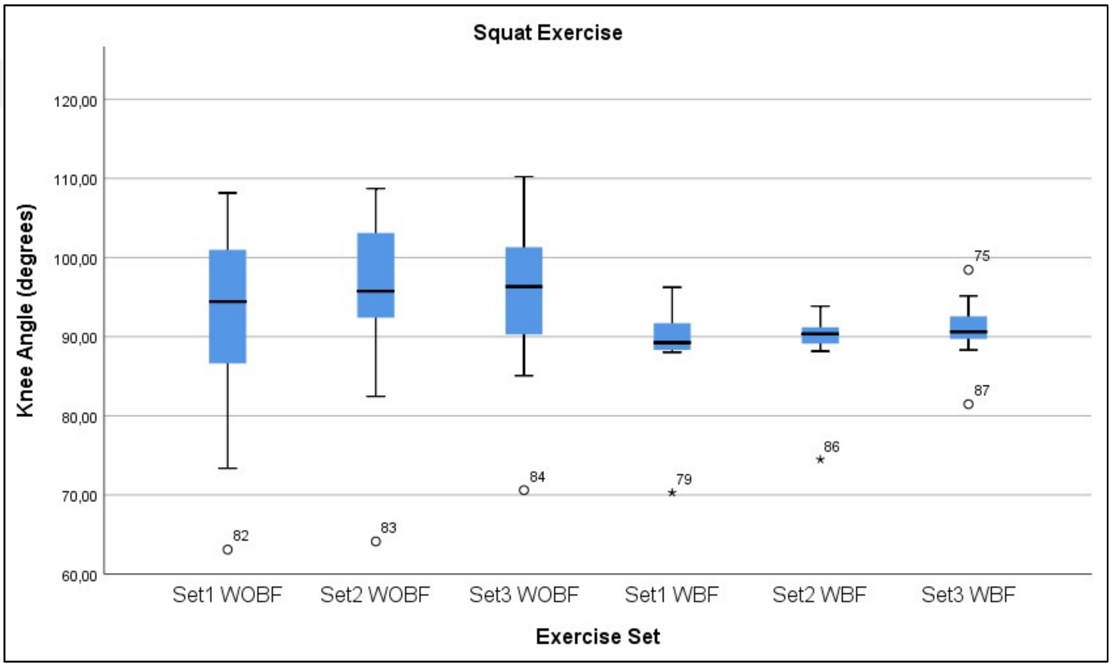


Figure 3.3. Squat exercise boxplot graph

Spearman correlation test results show that there is a very weak correlation in seated leg flexion/extension and sit-to-stand exercises, but there is a "moderate" strength correlation between squat exercises with statistical significance (Table 3.5).

Table 3.5. Correlations

	Seated Leg Flexion-Extension Exercise	Sit-to-Stand Exercise	Squat Exercise
Spearman's rho	0.07	-0.01	0.49
P	0.13	0.81	< 0.01

4. DISCUSSION

The current thesis work aims to improve the efficiency of knee-based exercises using audio biofeedback. Compared to open-chained exercise (seated leg flexion-extension), close-chained exercises (squat and sit-to-stand) show statistically significant improvements with the use of audio biofeedback. This improvement may be more drastic in exercises that movement does not end with locking motion of the knee (e.g., squat). Once a week, a total of two physical exercise sessions were performed by the volunteers. Three different knee-based physical exercises were done in both sessions. Two of these exercises were closed-chained exercises (squat and sit-to-stand) and one is an open-chained exercise (seated leg flexion/extension). Each exercise was done in three sets and each set consists of ten repetitions. To assess the effect of biofeedback during physical exercise, each volunteer executed one of the exercise sessions with audio biofeedback and the other without audio biofeedback. These sessions were randomly assigned for each volunteer. AB/BA crossover method was used to increase the randomization and to minimize the learning state of the body. Since all volunteers carried out the same exercise in both weeks, there was a chance that during the second week, the volunteer might have better performance due to learning and practicing the same exercise in the previous week. By randomizing the order of receiving audio feedback, the effect of audio feedback on learning the exercise and the state of having learned the exercise were all minimized.

To track and record knee movement and provide audio biofeedback during physical exercise, a system was designed. The knee is considered as a hinge-type synovial joint that mainly allows flexion, extension, and a small degree of medial and lateral motion. The system uses two BNO055 MEMS sensors placed on the lateral side of the knee thigh and shin for quantifying knee flexion-extension motion in the sagittal plane. Knee range of motion was acquired by acquiring the Quaternion output from both BNO055 sensors, converting Quaternion output to Euler angles, and finding the difference between Euler angle output in the sagittal plane. During the exercise session, both sensors give an output at the rate of 100 Hz, and depending on to change in knee joint angle, audio biofeedback is provided to the volunteers.

Each exercise has its movement pattern and phases that can be used as an input for tracking exercise progress by examining the changes in the knee joint angle values As the system understands that the motion completes by achieving all the desired movements, the system considers that 1 repetition of that exercise motion is completed. In addition, while receiving and tracking the quantified knee movement data, the system also provides audio biofeedback to the volunteers. The provided audio biofeedback is the repetition number, set number, achieved range of motion, starting and finishing of the exercise. Being an inexpensive feedback source with minimum hardware requirements, being able to customize the audio biofeedback, and bring ease to use are the three main advantages for choosing audio as biofeedback [31]. For audio biofeedback, since the system provides extrinsic feedback, knowledge of the result has been chosen. Terminal timing is used for audio biofeedback to examine the effect of audio biofeedback on physical exercise progress.

The addition of biofeedback provides a positive impact on volunteer's experience. In their review, they are satisfied and prefer to receive audio feedback during physical exercise. During their exercise session with biofeedback, volunteers are more motivated for doing physical exercise and this motivation is observed to be much higher during squat exercise since it is more challenging to achieve 90 degrees during squatting. This shows the benefits of audio biofeedback on morale. However, since all volunteers were healthy and managed to complete each exercise session without any problems, a separate study is needed to test the possible consequence of the drop in morale that results from reporting failure to progress in physical exercise. In addition, even SUS score is higher for the system with audio biofeedback, the difference is not statistically significant, although volunteers prefer audio feedback more. It is believed that the fact that the volunteers know the person who designed the system may affect scoring both systems high. It is believed that increase in the number of volunteers who will participate in the exercise and not knowing the system designer will create a significant difference between the two systems. The addition of audio biofeedback increases the accuracy and precision in squat and sit-to-stand exercises however, further investigation is needed with an increased number of volunteers and the system should be tested with more close-chained exercises.

The software of the thesis can only monitor the knee movement and give feedback depending on the change in the range of motion, the system cannot identify or distinguish the exercises. Since sit-to-stand and seated leg flexion-extension consists of the same movement pattern for the knee joint (from 90 degrees to 0 degrees) the system can provide accurate audio biofeedback however, it cannot differentiate which exercise is being done. Moreover, if a volunteer begins the exercise session with squat exercise, the system cannot able to provide accurate feedback. This setback can be solved by developing software that, while tracking exercise movement, the system understands which exercise is being performed based on the movement pattern.

In general, the exercise system work without any flow or problem during data collection. Volunteers were able to receive audio biofeedback without any problem and were able to equip and use the system in a few minutes. However, few improvements can be done. One of the most crucial improvements in the method of data collection and storage. Since the data is stored on an SD card, any problem or damage that occurred to it may result in losing the whole exercise data. To prevent this, after the end of each session, data of that session were stored in the cloud and also in a personal external hard disk. This method reduces the possibility of exercise data loss but it is a cumbersome method. Instead, direct data transfer to a computer by USB cable or wireless data transfer can be a better and safer method. Creating audio files was an easy task and provides a good opportunity for customizing the audio biofeedback, however creating a file for all numbers, guides, and commands for volunteers may also be a cumbersome task, a more practical method may be found for this. During the data collection, BNO055 provided good measurements without any drift but to receive correct output from both sensors, calibration is necessary. Calibrating BNO055 takes a little time and series of specific motions which may hamper the usage but, using previously recorded offset values can also be used for BNO055 calibration. To use offset values, the system must be used in the same environment. Also, while using sensors, using near an electronic device should be avoided since any magnetic field may cause drifting in the sensor output. During exercise, the output from sensors was compared with the long arm goniometer result and found a possible $\pm 1°$ change in angle. During data collection, only the primary rotation, rotation in the sagittal axis is recorded and used for tracking ROM and providing audio feedback, however during exercise, knee joint motion in the other two planes should also be examined since the knee joint has complex three-dimensional motion.

Modular leg straps are cheap, good quality and disposable options for wearable systems and they provide good stability but their quality may decrease with long-term usage. As an alternative to modular leg straps, adhesive tech may be used for testing different designs.

The two setbacks in the system design are cable connections between BNO055 and microcontroller, and power supply. The cable connections that were used for electrical connection between BNO055 sensors that were placed on the leg straps and the main unit that was placed on the waist, brought the risk of tangling and removing cable connection during exercise. This setback can be solved by improving the system with the use of a wireless connection between BNO055 and the main unit. The second setback is that the power is supplied to the system via a USB cable. This setback limits the usage of the system away from any power outlets or any electronics that provide +5Vdc to the system, but with the increase of usage and quality of portable power banks, this setback can easily be solved.

For comparative analysis, systems that use biofeedback on gait or balance analysis, visual biofeedback systems, and usage areas other than physical therapy of the knee are excluded. The systematic review for training with biofeedback after total knee arthroplasty (TKA), includes literature from inception to May 2018 and used “Biofeedback” or “Feedback” and “Total Knee Arthroplasty” or “TKA” keywords [29]. The review concludes that training with biofeedback after TKA provides gait symmetry improvement, pain reduction, and activity level increase. A total of eleven articles are found that focus on TKA using real-time biofeedback, nine of these articles reported significant improvements in activity score or pain [29]. Among these studies, six of them use visual feedback, the remaining four use combination of visual, haptic, and audio biofeedback, and one study use only audio biofeedback. The review can not answer which biofeedback method is best since there are unclear explanations for the reason of using visual biofeedback and only one study (Kuiken et al.) mention that audio biofeedback is more helpful for patients since it is hard for them to follow visual feedback without the usage of reading glasses. Almost all of the studies mentioned in the review used different variants of feedback devices. One of the most important and big differences is that the thesis system design is a wearable system however, most of the mentioned devices in the review were mostly balance board, or treadmill, only one of these studies used a system design that can be compared to our system as its design [29]. Kuiken et al. designed a goniometer-based, joint position biofeedback system that monitors the active range of motion [58]. A similar point of this design is that this system also has a similar wearable design. A main computerized system is placed on the waist which receives the knee joint ROM from the measuring unit and depending on the ROM reading, it provides biofeedback. However, instead of IMU, an electro goniometer was used and both audible and visual biofeedback were provided to encourage the user. The components of the audible biofeedback were also not clear [58].

The scoping review of "Feedback Design in Targeted Exercise Digital Biofeedback Systems for Home Rehabilitation" includes the studies of digital biofeedback systems for home-based targeted exercises, that tested on a clinical population from January 2000 to July 2019 [17]. 13 different biofeedback systems are identified for inclusion criteria in this review, of which 5 both auditory and visual biofeedback are applied. Two of them fit the comparative criteria [60, 61]. No study has been found that includes only auditory biofeedback.

In the study of Argent et al., the system focuses on exercises for post-operative knee ROM and strengthening [59]. The study is participated by 15 patients with a total knee replacement or unicompartmental knee replacement. The patients use the system at home for two weeks and then complete a semi-structured interview, SUS, and user version of the Mobile Application Rating Scale (uMARS). The system consists of a single IMU, Shimmer3 (Shimmer, Dublin, Ireland), and a tablet computer with a custom-built Android application. The data transfer is performed via Bluetooth to the tablet, and during exercise, the patient is guided through the visual biofeedback by the tablet. There is no clear explanation of exercise protocol implemented but from the illustrations presented the seated leg flexion-extension and straight leg raise seem to be the two exercises considered. The system provides audible biofeedback as a beeping noise for indicating repetitions and is reported to have high usability (overall SUS score = 90.8). However, the engagement section of "uMARS" has lower mean scores compared to its other sections. The reason for this is the lack of customization of sound, content, and notifications and the inability to set reminders and allow for interactivity [59]. Also from the reviews, there are some problems where the system sometimes misses the repetition counting [60].

In the study of Correia et al., post-operative knee ROM and strengthening after TKA are focused [60]. The study tests a novel digital biofeedback system (SWORD) that is designed for home-based rehabilitation. In the study, 10 sessions are done over two weeks. The most important aspect of the system is that it uses three IMU sensors. 2 of the sensors are placed on the thigh and shin and the third one place on the chest which is believed to allow the system to differentiate exercises and provide more detailed movement tracking. The connections of IMU are wireless via Bluetooth. The system also includes a tablet with a custom-made application. With the application, the users can track their progress through the tablet which displays, an avatar displaying the user's posture, a timer, and a repetition counter. Real-time feedback was supplied via a tablet with a custom-made application. The users are instructed visually and audibly through the system. The system also includes a great method of motivation: a ROM progress bar, which rewards stars. It is believed that this method of motivation created the same effect with the thesis system that provided knowledge of results as audio biofeedback [60]. Sixty-nine patients were included in this study and the exercises that were done: lying knee flexion, sitting knee extension and flexion, and standing knee flexion. The patient satisfaction was high and clinically significant improvements were seen with the usage of the system outcome. However, no statistically significant difference was found with system usage, and change in patient conditions during the study is believed to be related to this result being not statistically significant.

5. CONCLUSION

This thesis aimed to improve the efficiency of physical exercise of the knee with biofeedback. The addition of biofeedback improves accuracy and precision in sit-to-stand and squat exercises output and hence improves efficiency. The exercises that were done by the volunteers are considered as targeted exercise which consists of a great amount of repetitive movement. As mentioned before, these repetitive movements can result in improved recovery of the knee but the requirement of regularly executing targeted exercise and not having proper supervision can cause uncertainty and loss of interest [17]. The addition of biofeedback may reduce or eliminate these setbacks but for that, the method and design of the biofeedback should be planned thoroughly.

Poorly choosing the biofeedback method and design will result in a negative outcome for physical exercise. Usability is one of the main elements that decide the uptake of the system to the market. Using audio biofeedback in the exercise system provided a customizable, easy to use and effective method at motivating the volunteers and improving their exercise results. In the design of the audio biofeedback, there was no delay, no discomfort caused by it, and managed to inform the volunteers. The words that used in audio biofeedback during the physical exercise were directly related to the exercise. The sound and words used in audio biofeedback were found suitable by the volunteers, it was not dull or caused any confusion (29).

In future studies, the knee motion detecting system should be improved to differentiate the exercises by tracking and examining the exercise movement. To better understand the implications of audio feedback in influencing motor learning and user engagement in knee-based physical exercise, the designed system should be compared with other digital biofeedback systems that provide feedback as a visual, audible, or combination of both. In addition, compared to visual feedback, fewer articles and systems focused on audio feedback, and the absence of a systematic review about audio feedback systems offers possible new studies about audio feedback-based physical therapy. Testing the change in efficiency when the audio feedback is used by patients requiring physical therapy should be done in the further planned studies.

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APPENDIX A: ETHICS COMMITTEE DECISION LETTER

T.C. YEDİTEPE ÜNİVERSİTESİ
GİRİŞİMSEL OLMAYAN KLİNİK ARAŞTIRMALAR
ETİK KURULU

Versiyon No
1.0
Sayfa 1 / 2

KARAR FORMU

2.09.2021

ETİK KURUL BİLGİLERİ	Etik Kurulun Adı	Yeditepe Üniversitesi Girişimsel Olmayan Klinik Araştırmalar Etik Kurulu
	Açık Adres	Yeditepe Üniversitesi Diş Hekimliği Fakültesi, Bağdat Cad. No. 238 Göztepe 34728 Kadıköy, İstanbul
	İnternet Sayfası	http://goetik.yeditepe.edu.tr/
	Telefon	0216 363 60 44
	E-posta	goetik@yeditepe.edu.tr

DEĞERLENDİRİLEN BELGELER	Islak imzalı başvuru dosyası, CD'si ve elektronik başvuru	☒
	Araştırma başlığı ve araştırmacıların isimleri	☒
	Başvuru dilekçesi	☒
	Araştırmanın;	☒
	• Niteliği	☒
	• Önemi ve özgün değeri	☒
	• Amaç ve hedefleri	☒
	• Yöntemi	☒
	• Yönetimi	☒
	• Yaygın etkisi	☒
	• Araştırma bütçesi (Mevcutsa)	☒
	• Süresi ve uygunluğu (Zaman cetveli)	☒
	• Kaynakları	☒
	Araştırma izin belgesi / belgeleri	☒
	Bilgilendirilmiş Gönüllü Olur Formu (yapılan araştırmaya özel olarak hazırlanmış)	☒
	Taahhütname-1 Dünya Tıp Birliği Helsinki Bildirgesinin son versiyonunun ve Sağlık Bakanlığı'nın ilgili tüm kılavuzlarının okunmasına dair taahhüt	☒
	Taahhütname-2 Daha önce yapılmış etik kurul başvuruları mevcut olup olmadığına dair taahhüt	☒
	Taahhütname-3 Araştırma sırasında araştırma bütçesinde yer almayan ve gönüllünün kendisine veya Sosyal Güvenlik Kurumuna ek yük getirecek hiçbir işlem uygulanmayacağına dair taahhüt	☒
	Taahhütname-4 COVID-19 hastalarında tedavi yaklaşımları ve bilimsel araştırmalar genelgesi okunmasına dair taahhüt	☒
	Araştırmacıların her birisine ait özgeçmiş formu	☒
	Ek belgeler (Varsa kullanılan ölçek izinleri vb.)	☒

KARAR BİLGİLERİ	Başvuru Numarası	202104017
	Toplantı Tarihi	21.06.2021
	Toplantı Yeri	Çevirim içi (Google Meet)
	Karar No	9

Araştırmanın Başlığı **Biyogeribildirim Kullanarak Fiziksel Egzersizlerin Verimliliğinin Arttırılması**

Araştırmacılar **Doç. Dr. Gökhan Ertaş, Hayrettin Can Südor, Dr. Öğr. Üyesi Feyza Şule Badıllı, Ayça Yağcıoğlu**

T.C. YEDİTEPE ÜNİVERSİTESİ
GİRİŞİMSEL OLMAYAN KLİNİK ARAŞTIRMALAR
ETİK KURULU

Versiyon No 1.0
Sayfa 2 / 2

BAŞVURU NUMARASI: 202104017

KARAR 2.09.2021

☒ **KABUL**	☐ **RET** ☐ *KAPSAM DIŞI (GİRİŞİMSEL)* ☐ *BİLİMSEL VE/VEYA ETİK KURALLARA AYKIRI* ☐ *BİR SORUMLU ARAŞTIRMACININ (TEZ İSE TEZ DANIŞMANI), BİR TOPLANTIYA **İKİ (2) ADETTEN FAZLA ÇALIŞMA BAŞVURUSUNDA** BULUNMASI* ☐ *KURUM İÇİ BAŞVURULARINDA **YEDİTEPE UZANTILI E-POSTA HESABI** İLE GİRİŞ YAPILMAMIŞ OLMASI* ☐ *ŞARTLI KABULDE BELİRTİLEN REVİZYONLARIN ZAMANINDA VE/VEYA İSTENİLDİĞİ ŞEKİLDE YAPILMAMIŞ OLMASI*

Araştırmanın Başlığı	**Biyogeribildirim Kullanarak Fiziksel Egzersizlerin Verimliliğinin Arttırılması**
Araştırmacılar	**Doç. Dr. Gökhan Ertaş, Hayrettin Can Südor, Dr. Öğr. Üyesi Feyza Şule Badıllı, Ayça Yağcıoğlu**

APPENDIX B: SYSTEM SOFTWARE FOR EXERCISE SESSION WITH AUDIO BIOFEEDBACK

```
#include <Arduino.h>
#include <DFRobotDFPlayerMini.h>
#include <Wire.h>
#include <SPI.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_BNO055.h>
#include <utility/imumaths.h>
#include <SdFat.h>
#include <math.h>

#include <SoftwareSerial.h>

#define DEG (180/M_PI)
#define BNO055_SAMPLERATE_DELAY_MS (100)
const uint32_t SAMPLE_INTERVAL_MS = 100;

// File system object.
SdFat sd;
// Log file.
SdFile file;
const int chipSelect = 3;
char filename[16];
String dataString = "";
unsigned long dataReadTime = 0;

float yaw1  = 0.00;
float roll1 = 0.00;
float yaw2  = 0.00;
float roll2 = 0.00;
/*************************Units for SD data***********************/
float data = 0;
unsigned long previousMillis = 0;
unsigned long start = 0;
/*********************************************************************
**
//Egzersiz sırasında kullanılanlar
const int buttonPin = 0;
int reading;
int previous = LOW;
long time = 0;
long debounce = 200;
int waiting = HIGH;

int idleCounter = 0;
byte Control = 0;
int interval = 1000;
unsigned long slavesound;
int tick = 0;
float angle = 0.00;
float min_pitch = 99.99;
float max_pitch = 0.00;
int exercise = 1; // used to track which exercise will be done
int sets = 1;
int rep = 0;
```

```
float flx_angles[] = {99, 99, 99, 99, 99, 99, 99, 99, 99, 99};
float sts_angles[] = {99, 99, 99, 99, 99, 99, 99, 99, 99, 99};
float sqt_angles[] = {0, 0, 0, 0, 0, 0, 0, 0, 0, 0};

int audioAngle = 0; //used to tell min/max angle of the current rep

Adafruit_BNO055 bno1 = Adafruit_BNO055(1, BNO055_ADDRESS_A);
Adafruit_BNO055 bno2 = Adafruit_BNO055(2, BNO055_ADDRESS_B);

SoftwareSerial mySoftwareSerial(1, 2); // RX, TX
DFRobotDFPlayerMini myDFPlayer;

void setup() {
  // initialize the pushbutton pin as an input:
  pinMode(buttonPin, INPUT_PULLUP);
  //digitalWrite(buttonPin, HIGH);
  delay(2000);
  Serial.println("Greetings");

  Serial.begin(9600);
  mySoftwareSerial.begin(9600);

  /** DFPLAYER SETUP **********************************/
  Serial.println();
  Serial.println(F("DFRobot DFPlayer Mini Demo"));
  delay(500);
  Serial.println(F("Initializing DFPlayer ... (May take 3~5
seconds)"));

  if (!myDFPlayer.begin(mySoftwareSerial)) {
    Serial.println(F("Unable to begin:"));
    Serial.println(F("1.Please recheck the connection!"));
    Serial.println(F("2.Please insert the SD card!"));
    while (true);
  }

  myDFPlayer.volume(20);  //Set volume value. From 0 to 30
  byte f = 2;
  int folder = (int)f;
  byte t = 1;
  Serial.println(folder);
  delay(100);
  int track = (int)t;
  Serial.println(track);
  myDFPlayer.playFolder(1, 66);
  delay(1000);

  /** BNO055 CALIBRATION ************************************/
  if (bno1.begin()) {
        myDFPlayer.playFolder(1, 3);
        delay(500);
        displayCalStatus1();//Kalibrasyon 1
  }
  else {
    /* Problem detecting the BNO055 ... check your connections */
    myDFPlayer.playFolder(1, 2);
    delay(500);
    Serial.print("Ooops, first BNO055 not detected ... Check wiring");
    while (1);
  }
```

```
  if (bno2.begin()) {
    //myDFPlayer.playFolder(1, 4);
    //displayCalStatus2();//Kalibrasyon 2
  }
  else {
    /* Problem detecting the BNO055 ... check your connections */
    myDFPlayer.playFolder(1, 2);
    delay(500);
    Serial.print("Ooops, second BNO055 not detected ... Check wiring");
  }

  //Calibrating the sensors
  uint8_t system, gyro, accel, mag = 0;
  //Gyro != 3 is calibration for IMU, System!=3 is calibration for NDOF
  while (gyro != 3) {
    bno1.getCalibration(&system, &gyro, &accel, &mag);
    bno2.getCalibration(&system, &gyro, &accel, &mag);
  }

  bno1.setMode(Adafruit_BNO055::OPERATION_MODE_NDOF);
  bno1.setExtCrystalUse(true);
  bno2.setMode(Adafruit_BNO055::OPERATION_MODE_NDOF);
  bno2.setExtCrystalUse(true);
  delay(100);

  /***************************SD Initialise ***********************/
  // Initialize the SD card at SPI_HALF_SPEED to avoid bus errors with
  if (!sd.begin(chipSelect)) {
    Serial.println(F("initialization failed!"));
    exit(0);
  }
  Serial.println("Initialization successful");

  /*********************************************************************/
  myDFPlayer.playFolder(1, 6); // "Please press the button command"
  delay(2000);
  dataReadTime = millis();
}
void loop() {

  while (sets < 4) {
    Serial.println("Press the button when ready.");
    delay(500);
    while (waiting == HIGH) {
      idleData();
      pushButton();
    }
    createFile();
    legFlexion();
    sets++;
    Serial.println("set bitti.");
    file.close();
    myDFPlayer.playFolder(4, sets);
    delay(4000);
  }

  sets = 1; // clear sets for the next exercise
  exercise++;
  Serial.println("1. egzersiz bitti.");
  myDFPlayer.playFolder(1, 8);
```

```
  delay(3000);
  /**************************************************/
  while (sets < 4) {
    Serial.println("Press the button when ready.");
    delay(500);
    while (waiting == HIGH) {
      idleData();
      pushButton();
    }
    createFile();
    sitToStand();
    sets++;
    Serial.println("set bitti.");
    file.close();
    myDFPlayer.playFolder(4, sets);
    delay(4000);
  }

  sets = 1; // clear sets for the next exercise
  exercise++;
  Serial.println("2. egzersiz bitti.");
  myDFPlayer.playFolder(1, 8);
  delay(3000);
  /**************************************************/
  while (sets < 4) {
    Serial.println("Press the button when ready.");
    delay(500);
    while (waiting == HIGH) {
      idleData();
      pushButton();
    }
    createFile();
    squat();
    sets++;
    Serial.println("set bitti.");
    file.close();
    myDFPlayer.playFolder(4, sets);
    delay(3000);
  }

  Serial.println("Bütün egzersizlerin bitti.");
  myDFPlayer.playFolder(1, 9);
  delay(3000);

  exit(0);
}


void legFlexion(void) {

  myDFPlayer.playFolder(1, 11);
  delay(500);
  start = millis();
  while (rep < 10 && waiting == LOW) {

    if (Control == 1) {
      if (millis() - slavesound > interval) {
        Control = 0;
        myDFPlayer.pause();
      }
```

```
    }
    getValues();
    if (angle < 35.0 ) {
      min_pitch = min(angle, min_pitch);
      if (tick == 0) {
        tick = 1;
        myDFPlayer.playFolder(2, rep + 1);
      }
    }

    if (angle >= 50.0 && Control == 0 && tick == 1) {
      //Serial.println("uyarı!");
      flx_angles[rep] = min_pitch;
      rep++;
      tick = 0;
      Control = 1;
      slavesound = millis();
      audioAngle = round(min_pitch);
      myDFPlayer.playFolder(3, audioAngle + 1);

      min_pitch = 99.9;
    }
    pushButton();

  }
  waiting = HIGH;
  file.println("Values:");
  for (int i = 0; i < 10; i++) {
    String valueString = String(flx_angles[i]);
    file.println(valueString);
  }
  file.println();
  rep = 0;

}

void sitToStand(void) {

  myDFPlayer.playFolder(1, 12);
  delay(500);
  start = millis();
  while (rep < 10 && waiting == LOW) {

    if (Control == 1) {
      if (millis() - slavesound > interval) {
        Control = 0;
        myDFPlayer.pause();
      }
    }
    getValues();
    if (angle < 35.0) {
      min_pitch = min(angle, min_pitch);
      if (tick == 0) {
        tick = 1;
        myDFPlayer.playFolder(2, rep + 1);
      }
    }

    if ((angle) >= 60.0 && Control == 0 && tick == 1) {
      sts_angles[rep] = min_pitch;
```

```
      rep++;
      tick = 0;
      Control = 1;
      slavesound = millis();
      audioAngle = round(min_pitch);
      myDFPlayer.playFolder(3, audioAngle + 1);
      min_pitch = 99.9;
    }
    pushButton();
  }
  waiting = HIGH;
  file.println("Values:");
  for (int i = 0; i < 10; i++) {
    String valueString = String(sts_angles[i]);
    file.println(valueString);
  }
  file.println();
  rep = 0;

}

void squat(void) {

  myDFPlayer.playFolder(1, 13);
  delay(500);
  start = millis();
  while (rep < 10 && waiting == LOW) {

    if (Control == 1) {
      if (millis() - slavesound > interval) {
        Control = 0;
        //myDFPlayer.pause();
      }
    }
    getValues();
    if (angle > 60.0) {
      max_pitch = max(angle, max_pitch);
      if (tick == 0) {
        tick = 1;
        myDFPlayer.playFolder(2, rep + 1);

      }
    }

    if ((angle) <= 25.0 && Control == 0 && tick == 1) {
      sqt_angles[rep] = max_pitch;
      rep++;
      tick = 0;
      Control = 1;
      slavesound = millis();
      audioAngle = round(90 - max_pitch);
      myDFPlayer.playFolder(3, audioAngle + 1);
      Serial.print("Angle: ");
      Serial.println(audioAngle);
      max_pitch = 0.00;
    }
    pushButton();
  }
  waiting = HIGH;
  file.println("Values:");
```

```
  for (int i = 0; i < 10; i++) {
    String valueString = String(sqt_angles[i]);
    file.println(valueString);
  }
  file.println();
  rep = 0;

}
void idleData(void)
{
/** Primary Sensor***********************************/
  sensors_event_t event;

  bno1.getEvent(&event);
  imu::Quaternion quat1 = bno1.getQuat();
  quat1.normalize();
  //  Serial.print("YAW1: ");
  //  Serial.print(event.orientation.x, 4);
  //  Serial.print(F(" "));
  //
  //  Serial.print("\tPITCH1: ");
  //  Serial.print(event.orientation.y, 4);
  //  Serial.print(F(" "));
  //
  //  Serial.print("\tROLL1: ");
  //  Serial.print(event.orientation.z, 4);
  //  Serial.print(F(" "));

  imu::Vector<3> euler1 = quat1.toEuler();
  roll1 = (euler1[2] * DEG);

  /** Secondary Sensor***********************************/
  bno2.getEvent(&event);
  imu::Quaternion quat2 = bno2.getQuat();
  quat2.normalize();

  imu::Vector<3> euler2 = quat2.toEuler();
  roll2 = (euler2[2] * DEG);

  angle = abs((roll1) - (roll2));
  Serial.print(roll1);    Serial.print("\t");
  Serial.print(roll2);    Serial.print("\t");
  Serial.print("angle:"); Serial.println(angle);
  //  idleCounter++;
  //  if (idleCounter == 6) {
  //    idleCounter = 0;
  //    audioAngle = round(angle);
  //    myDFPlayer.playFolder(3, audioAngle + 1);
  //  }
  delay(500);
}

void getValues(void)
{
  sensors_event_t event;

  bno1.getEvent(&event);
  imu::Quaternion quat1 = bno1.getQuat();
  imu::Vector<3> euler1 = quat1.toEuler();
  roll1 = (euler1[2] * DEG);
```

```
  bno2.getEvent(&event);
  imu::Quaternion quat2 = bno2.getQuat();
  imu::Vector<3> euler2 = quat2.toEuler();
  roll2 = (euler2[2] * DEG);

  angle = abs((roll1) - (roll2));
  Serial.print(roll1); Serial.print("\t");
  Serial.print(roll2); Serial.print("\t");
  Serial.print("angle:"); Serial.println(angle);

  logData(roll1,roll2,angle);
}

void logData(float data1, float data2, float dataAngle)
{
  unsigned long CurrentMillis = millis();
  unsigned long duration = CurrentMillis - start;

  String dataString = String(duration) + ", " + String(data1)+ ", " +
String(data2)+ ", " + String(dataAngle);
  //String dataString = String(data);
  file.println(dataString);
  if (CurrentMillis - previousMillis >= 10000) {
    file.flush();
    previousMillis = CurrentMillis;
  }
}

void createFile (void) {

  if (exercise == 1 && sets == 1) {
    if (!file.open("data1.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Opening data1.csv failed"));
    }
    else {   Serial.println(F("File opened"));
    }
  }
  else if (exercise == 1 && sets == 2) {
    if (!file.open("data2.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Opening data2.csv failed"));
    }
    else {  Serial.println(F("File opened"));
    }
  }
  else if (exercise == 1 && sets == 3) {
    if (!file.open("data3.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Opening data3.csv failed"));
    }
    else {  Serial.println(F("File opened"));
    }
  }
  else if (exercise == 2 && sets == 1) {
    if (!file.open("data4.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened"));
    }
  }
  else if (exercise == 2 && sets == 2) {
```

```
    if (!file.open("data5.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened"));
    }
  }
  else if (exercise == 2 && sets == 3) {
    if (!file.open("data6.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened")); }
  }
  else if (exercise == 3 && sets == 1) {
    if (!file.open("data7.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened"));
    }
  }
  else if (exercise == 3 && sets == 2) {
    if (!file.open("data8.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened"));
    }
  }
  else if (exercise == 3 && sets == 3) {
    if (!file.open("data9.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened"));
    }
  }
}

void pushButton()
{
  reading = digitalRead(buttonPin);
  if (reading == HIGH && previous == LOW && millis() - time > debounce)
{
    if (waiting == HIGH)
      waiting = LOW;
    else
      waiting = HIGH;
    Serial.print("input: "); Serial.print(reading); Serial.print("\t");
    Serial.print("previous: ");
    Serial.println(previous);
    Serial.print("Waiting:");
    Serial.println(waiting);
    time = millis();
  }
  previous = reading;
}

void displayCalStatus1(void)
{
  /* Get the four calibration values (0..3) */
  /* Any sensor data reporting 0 should be ignored, */
  /* 3 means 'fully calibrated" */
  uint8_t system, gyro, accel, mag;
```

```
  system = gyro = accel = mag = 0;

  while (1) {
    bno1.getCalibration(&system, &gyro, &accel, &mag);
    /* The data should be ignored until the system calibration is > 0
*/
    Serial.print("\t");
    if (!system)
    {
      Serial.print("! ");
    }

    /* Display the individual values */
    Serial.print("Sys:");     Serial.print(system, DEC);
    Serial.print(" G1:");     Serial.print(gyro, DEC);
    Serial.print(" A1:");     Serial.print(accel, DEC);
    Serial.print(" M:");      Serial.println(mag, DEC);
    delay(100);

    if (system == 3 && gyro == 3 && accel == 3 && mag == 3) {
      Serial.println("Calibration successful");
      myDFPlayer.playFolder(1, 5);
      break;
    }
  }
}
void displayCalStatus2(void)
{
  /* Get the four calibration values (0..3) */
  /* Any sensor data reporting 0 should be ignored, */
  /* 3 means 'fully calibrated" */
  uint8_t system, gyro, accel, mag;
  system = gyro = accel = mag = 0;

  while (1) {
    bno2.getCalibration(&system, &gyro, &accel, &mag);
    /* The data should be ignored until the system calibration is > 0
*/
    Serial.print("\t");
    if (!system)
    {
      Serial.print("! ");
    }

    /* Display the individual values */
    Serial.print("Sys:");Serial.print(system, DEC);
    Serial.print(" G:"); Serial.print(gyro, DEC);
    Serial.print(" A:"); Serial.print(accel, DEC);
    Serial.print(" M:"); Serial.println(mag, DEC);
    delay(100);
    if (system == 3 && gyro == 3 && accel == 3 && mag == 3) {
      Serial.println("Calibration successful");
      myDFPlayer.playFolder(1, 5);
      break;
    }
  }
}
```

APPENDIX C: SYSTEM SOFTWARE FOR EXERCISE SESSION WITHOUT BIOFEEDBACK

```
#include <Arduino.h>
#include "DFRobotDFPlayerMini.h"
#include <Wire.h>
#include <SPI.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_BNO055.h>
#include <utility/imumaths.h>
#include <SdFat.h>
#include <math.h>

#include <SoftwareSerial.h>

#define DEG (180/M_PI)
#define BNO055_SAMPLERATE_DELAY_MS (100)
const uint32_t SAMPLE_INTERVAL_MS = 100;

SdFat sd;
SdFile file;
const int chipSelect = 3;
char filename[16];
String dataString = "";
unsigned long dataReadTime = 0;

float yaw1 = 0.00;
float roll1 = 0.00;
float yaw2 = 0.00;
float roll2 = 0.00;
/** SD dataları için birimler, yarın kontrol
et*************************/
float data = 0;
unsigned long previousMillis = 0;
unsigned long start = 0;
/**** *******/
//Egzersiz sırasında kullanılanlar
const int buttonPin = 0; // the number of the input pin
int reading;             // the current reading from the input pin
int previous = LOW;      // the previous reading from the input pin
long time = 0;           // the last time the output pin was toggled
long debounce = 200;     // the debounce time, increase if the output
flickers
int waiting = HIGH;

int idleCounter = 0; // used to wait idle to tell angles
byte Control = 0;
int interval = 1000;
unsigned long slavesound;
int tick = 0;
float angle = 0.00;
float min_pitch = 99.99;
float max_pitch = 0.00;
int exercise = 1; // used to track which exercise will be done
int sets = 1;
int rep = 0;
float flx_angles[] = {99, 99, 99, 99, 99, 99, 99, 99, 99, 99};
```

```
float sts_angles[] = {99, 99, 99, 99, 99, 99, 99, 99, 99, 99};
float sqt_angles[] = {0, 0, 0, 0, 0, 0, 0, 0, 0, 0};
int audioAngle = 0;   //used to tell min/max angle of the current rep
/*******************************************************************/

Adafruit_BNO055 bno1 = Adafruit_BNO055(1, BNO055_ADDRESS_A);
Adafruit_BNO055 bno2 = Adafruit_BNO055(2, BNO055_ADDRESS_B);
SoftwareSerial mySoftwareSerial(1, 2); // RX, TX
DFRobotDFPlayerMini myDFPlayer;
//void printDetail(uint8_t type, int value);

void setup() {
  // initialize the pushbutton pin as an input:
  pinMode(buttonPin, INPUT_PULLUP);
  //digitalWrite(buttonPin, HIGH);
  delay(2000);
  Serial.println("Greetings");

  Serial.begin(9600);
  mySoftwareSerial.begin(9600);

  /** DFPLAYER SETUP **********************************/
  Serial.println();
  Serial.println(F("DFRobot DFPlayer Mini Demo"));
  delay(500);
  Serial.println(F("Initializing DFPlayer ... (May take 3~5
seconds)"));

  if (!myDFPlayer.begin(mySoftwareSerial)) {
    Serial.println(F("Unable to begin:"));
    Serial.println(F("1.Please recheck the connection!"));
    Serial.println(F("2.Please insert the SD card!"));
    while (true);
  }

  myDFPlayer.volume(20);  //Set volume value. From 0 to 30
  byte f = 2;
  int folder = (int)f;
  byte t = 1;
  Serial.println(folder);
  delay(100);
  int track = (int)t;
  Serial.println(track);
  myDFPlayer.playFolder(1, 66);
  delay(1000);

  /** BNO055 CALIBRATION ************************************/
  if (bno1.begin()) {
        myDFPlayer.playFolder(1, 3);
        delay(500);
    displayCalStatus1();//Kalibrasyon 1
  }
  else {
    myDFPlayer.playFolder(1, 2);
    delay(500);
    Serial.print("Ooops, first not BNO055 detected ... Check your
wiring or I2C ADDR!");
    while (1);
  }
  if (bno2.begin()) {
```

```
    myDFPlayer.playFolder(1, 4);
    displayCalStatus2();//Kalibrasyon 2
  }
  else {
    myDFPlayer.playFolder(1, 2);
    delay(500);
    Serial.print("Ooops, second BNO055 not detected ... Check your
wiring or I2C ADDR!");
  }

  //Calibrating the sensors
  uint8_t system, gyro, accel, mag = 0;
  //Gyro != 3 is calibration for IMU, and System!=3 is calibration for
NDOF
  while (gyro != 3) {
    bno1.getCalibration(&system, &gyro, &accel, &mag);
    bno2.getCalibration(&system, &gyro, &accel, &mag);
  }

  bno1.setMode(Adafruit_BNO055::OPERATION_MODE_NDOF);
  bno1.setExtCrystalUse(true);
  bno2.setMode(Adafruit_BNO055::OPERATION_MODE_NDOF);
  bno2.setExtCrystalUse(true);
  delay(100);
  /***************************SD Initialise ***********************/
  if (!sd.begin(chipSelect)) {
    Serial.println(F("initialization failed!"));
    exit(0);
  }
  Serial.println("Initialization successful");

  /*****************************************************************/
  myDFPlayer.playFolder(1, 6); // "Hazır olduğunuzda lütfen düğmeye
basınız komutu"
  delay(2000);
  dataReadTime = millis();
}
void loop() {

  while (sets < 4) {
    Serial.println("Press the button when ready.");
    delay(500);
    while (waiting == HIGH) {
      idleData();
      pushButton();
    }
    createFile();
    unsigned long start = millis();
    legFlexion();
    sets++;
    Serial.println("set bitti.");
    file.close();
    myDFPlayer.playFolder(4, sets);
    delay(4000);
  }

  sets = 1; // clear sets for the next exercise
  exercise++;
  Serial.println("1. egzersiz bitti.");
  myDFPlayer.playFolder(1, 8);
```

```
  delay(3000);
  /*************************************************/
  while (sets < 4) {
    Serial.println("Press the button when ready.");
    delay(500);
    while (waiting == HIGH) {
      idleData();
      pushButton();
    }
    createFile();
    unsigned long start = millis();
    sitToStand();
    sets++;
    Serial.println("set bitti.");
    file.close();
    myDFPlayer.playFolder(4, sets);
    delay(4000);
  }

  sets = 1; // clear sets for the next exercise
  exercise++;
  Serial.println("2. egzersiz bitti.");
  myDFPlayer.playFolder(1, 8);
  delay(3000);
  /*************************************************/
  while (sets < 4) {
    Serial.println("Press the button when ready.");
    delay(500);
    while (waiting == HIGH) {
      idleData();
      pushButton();
    }
    createFile();
    unsigned long start = millis();
    squat();
    sets++;
    Serial.println("set bitti.");
    file.close();
    myDFPlayer.playFolder(4, sets);
    delay(3000);
  }

  Serial.println("Bütün egzersizlerin bitti, helal.");
  myDFPlayer.playFolder(1, 9);
  delay(3000);

  exit(0);
}


void legFlexion(void) {

  myDFPlayer.playFolder(1, 11);
  delay(500);
  while (rep < 10 && waiting == LOW) {

    if (Control == 1) {
      if (millis() - slavesound > interval) {
        Control = 0;
        myDFPlayer.pause();
```

```
      }
    }
    getValues();
    if (angle < 35.0 ) {
      min_pitch = min(angle, min_pitch);
      if (tick == 0) {
        tick = 1;
      }
    }

    if (angle >= 50.0 && Control == 0 && tick == 1) {
      //Serial.println("uyarı!");
      flx_angles[rep] = min_pitch;
      rep++;
      tick = 0;
      Control = 1;
      slavesound = millis();

      min_pitch = 99.9;
    }
    pushButton();

  }
  waiting = HIGH;
  file.println("Values:");
  for (int i = 0; i < 10; i++) {
    String valueString = String(flx_angles[i]);
    file.println(valueString);
  }
  file.println();
  rep = 0;

}

void sitToStand(void) {

  myDFPlayer.playFolder(1, 12);
  delay(500);
  while (rep < 10 && waiting == LOW) {

    if (Control == 1) {
      if (millis() - slavesound > interval) {
        Control = 0;
        myDFPlayer.pause();
      }
    }
    getValues();
    if (angle < 35.0) {
      min_pitch = min(angle, min_pitch);
      if (tick == 0) {
        tick = 1;
      }
    }

    if ((angle) >= 60.0 && Control == 0 && tick == 1) {
      sts_angles[rep] = min_pitch;
      rep++;
      tick = 0;
      Control = 1;
      min_pitch = 99.9;
```

```
    }
    pushButton();
  }
  waiting = HIGH;
  file.println("Values:");
  for (int i = 0; i < 10; i++) {
    String valueString = String(sts_angles[i]);
    file.println(valueString);
  }
  file.println();
  rep = 0;

}

void squat(void) {

  myDFPlayer.playFolder(1, 13);
  delay(500);
  while (rep < 10 && waiting == LOW) {

    if (Control == 1) {
      if (millis() - slavesound > interval) {
        Control = 0;
        //myDFPlayer.pause();
      }
    }
    getValues();
    if (angle > 60.0) {
      max_pitch = max(angle, max_pitch);
      if (tick == 0) {
        tick = 1;
      }
    }

    if ((angle) <= 25.0 && Control == 0 && tick == 1) {
      sqt_angles[rep] = max_pitch;
      rep++;
      tick = 0;
      Control = 1;
      Serial.print("Angle: ");
      Serial.println(audioAngle);
      max_pitch = 0.00;
    }
    pushButton();
  }
  waiting = HIGH;
  file.println("Values:");
  for (int i = 0; i < 10; i++) {
    String valueString = String(sqt_angles[i]);
    file.println(valueString);
  }
  file.println();
  rep = 0;


}
void idleData(void)
{
  /***Primary Sensor**********************************/
  sensors_event_t event;
```

```
  bno1.getEvent(&event);
  imu::Quaternion quat1 = bno1.getQuat();
  quat1.normalize();

  imu::Vector<3> euler1 = quat1.toEuler();
  roll1 = (euler1[2] * DEG);

  /** Secondary Sensor***********************************/
  bno2.getEvent(&event);
  imu::Quaternion quat2 = bno2.getQuat();
  quat2.normalize();

  imu::Vector<3> euler2 = quat2.toEuler();
  roll2 = (euler2[2] * DEG);

  angle = abs((roll1) - (roll2));
  Serial.print(roll1);
  Serial.print("\t");
  Serial.print(roll2);
  Serial.print("\t");
  Serial.print("angle:");
  Serial.println(angle);
  delay(500);
}

void getValues(void)
{
  sensors_event_t event;

  bno1.getEvent(&event);
  imu::Quaternion quat1 = bno1.getQuat();
  imu::Vector<3> euler1 = quat1.toEuler();
  roll1 = (euler1[2] * DEG);

  bno2.getEvent(&event);
  imu::Quaternion quat2 = bno2.getQuat();
  imu::Vector<3> euler2 = quat2.toEuler();
  roll2 = (euler2[2] * DEG);

  angle = abs((roll1) - (roll2));
  Serial.print(roll1);
  Serial.print("\t");
  Serial.print(roll2);
  Serial.print("\t");
  Serial.print("angle:");
  Serial.println(angle);
  logData(roll1,roll2,angle);
}

void logData(float data1, float data2, float dataAngle)
{
  unsigned long CurrentMillis = millis();
  unsigned long duration = CurrentMillis - start;

  String dataString = String(duration) + ", " + String(data1)+ ", " +
String(data2)+ ", " + String(dataAngle);

  file.println(dataString);
  //Serial.println(dataString);
```

```
  if (CurrentMillis - previousMillis >= 10000) {
    file.flush();
    previousMillis = CurrentMillis;
  }
}

void createFile (void) {

  if (exercise == 1 && sets == 1) {
    if (!file.open("data1.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Opening data1.csv failed"));
    }
    else {
      Serial.println(F("File opened"));
    }
  }
  else if (exercise == 1 && sets == 2) {
    if (!file.open("data2.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Opening data2.csv failed"));
    }
    else {
      Serial.println(F("File opened"));
    }
  }
  else if (exercise == 1 && sets == 3) {
    if (!file.open("data3.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Opening data3.csv failed"));
    }
    else {
      Serial.println(F("File opened"));
    }
  }
  else if (exercise == 2 && sets == 1) {
    if (!file.open("data4.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {
      Serial.println(F("File opened"));
    }
  }
  else if (exercise == 2 && sets == 2) {
    if (!file.open("data5.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened"));  }
  }
  else if (exercise == 2 && sets == 3) {
    if (!file.open("data6.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened"));  }
  }
  else if (exercise == 3 && sets == 1) {
    if (!file.open("data7.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened"));  }
  }
  else if (exercise == 3 && sets == 2) {
    if (!file.open("data8.csv", O_CREAT | O_WRITE | O_APPEND)) {
```

```
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened"));  }
  }
  else if (exercise == 3 && sets == 3) {
    if (!file.open("data9.csv", O_CREAT | O_WRITE | O_APPEND)) {
      Serial.println(F("Open failed"));
    }
    else {  Serial.println(F("File opened"));  }
  }
}

void pushButton()
{
  reading = digitalRead(buttonPin);
  if (reading == HIGH && previous == LOW && millis() - time > debounce)
{
    if (waiting == HIGH)
      waiting = LOW;
    else
      waiting = HIGH;
    Serial.print("input: ");
    Serial.print(reading);
    Serial.print("\t");
    Serial.print("previous: ");
    Serial.println(previous);
    Serial.print("Waiting:");
    Serial.println(waiting);
    time = millis();
  }
  previous = reading;

}

void displayCalStatus1(void)
{
  uint8_t system, gyro, accel, mag;
  system = gyro = accel = mag = 0;

  while (1) {
    bno1.getCalibration(&system, &gyro, &accel, &mag);
    /* The data should be ignored until the system calibration is > 0
*/
    Serial.print("\t");
    if (!system)
    {
      Serial.print("! ");
    }

    /* Display the individual values */
    Serial.print("Sys:");
    Serial.print(system, DEC);
    Serial.print(" G1:");
    Serial.print(gyro, DEC);
    Serial.print(" A1:");
    Serial.print(accel, DEC);
    Serial.print(" M:");
    Serial.println(mag, DEC);
    delay(100);
    if (system == 3 && gyro == 3 && accel == 3 && mag == 3) {
```

```
      Serial.println("Calibration successful");
      myDFPlayer.playFolder(1, 5);
      break;
    }
  }
}
void displayCalStatus2(void)
{
  uint8_t system, gyro, accel, mag;
  system = gyro = accel = mag = 0;

  while (1) {
    bno2.getCalibration(&system, &gyro, &accel, &mag);
    /* The data should be ignored until the system calibration is > 0
*/
    Serial.print("\t");
    if (!system)
    {
      Serial.print("! ");
    }

    /* Display the individual values */
    Serial.print("Sys:");
    Serial.print(system, DEC);
    Serial.print(" G:");
    Serial.print(gyro, DEC);
    Serial.print(" A:");
    Serial.print(accel, DEC);
    Serial.print(" M:");
    Serial.println(mag, DEC);
    delay(100);
    if (system == 3 && gyro == 3 && accel == 3 && mag == 3) {
      Serial.println("Calibration successful");
      myDFPlayer.playFolder(1, 5);
      break;
    }
  }
}
```