UNIVERSIDAD DE INVESTIGACIÓN DE TECNOLOGÍA EXPERIMENTAL YACHAY

Escuela de Ciencias Biológicas e Ingenierías

Título: Low-cost System for Wrist Rehabilitation and Treatment

Trabajo de integración curricular presentado como requisito para la obtención
del título de Ingeniero biomédico

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This project is dedicated to my parents Nancy and Patrico, my grandparents, George, Miriam, Esperanza and Monfilio, to all my familiy, and specially to my brothers Andrés and Elian who were my inspiration to keep going.

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Resumen

En el Ecuador no existen empresas o firmas relacionadas con el montaje y programación de sistemas orientados a la rehabilitación física. Y al menos en el sector público no hay departamentos de ingeniería orientados a esto o que se hayan destacado a nivel nacional y enfocados a la rehabilitación de la muñeca. De ahí la necesidad de proveer herramientas accesibles y de bajo costo para los fisioterapeutas que sean de código abierto y que les permitan adaptarse a sus necesidades y objetivos para facilitar el involucramiento y participación del paciente. Para ello se desarrolló un sistema basado en sensores inerciales, cuyos datos son tomados por un sistema basado en el lenguaje de programación Python para su posterior procesamiento y análisis. Este sistema basado en Python contiene la interfaz gráfica, así como un sistema de visualización tridimensional basado en el desarrollo de los Juegos Serios. El sistema desarrollado puede utilizarse para evaluar el tipo básico de movimiento de muñeca realizado, así como una herramienta para almacenar la información del paciente en una base de datos para facilitar la tarea del fisioterapeuta. Esto proporciona una herramienta de bajo costo (± 30) y fácil de usar y personalizar. En futuros trabajos el sistema se implementará con otros tipos de sensores de mayor precisión y al ser un sistema construido a partir de instrumentos electrónicos básicos se pueden añadir otros tipos de sensores para mejorar los tratamientos, así como para su uso en telerehabilitación.

Palabras clave: sensores inerciales, bajo costo, juegos serios, rehabilitación, Python, Arduino

Abstract

In Ecuador there are no companies or firms related to the assembly and programming of systems oriented to physical rehabilitation. And at least in the public sectors there are no engineering departments oriented to this or that have stood out nationally and focused on wrist rehabilitation. From this, the need arises to provide accessible and low cost tools for physical therapists that are open source and allow them to adapt to their needs and aims to facilitate patient involvement. This is why a system based on inertial sensors was developed, whose data is taken by a system based on the Python programming language for its later processing and analysis. This Python-based system contains the graphic interface, as well as a three-dimensional visualization system based on the development of the Serious Games. The developed system can be used to evaluate the basic type of wrist movement performed, as well as a tool to store patient information in a database to facilitate the task of the physiotherapist. This provides a low cost tool (± $30) and easy to use and customize. In future works the system will be implemented with other types of sensors of greater accuracy and being a system built from basic electronic instruments other types of sensors can be added to improve the treatments, as well as for its use in telerehabilitation.
Keywords: inertial sensors, low-cost, serious games, rehabilitation, Python, Arduino

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The wrist joint plays an important role in the performance of daily activities. Different pathologies or injuries can contribute to a reduction in its abilities. Historically, wrist injuries have been treated by amputation, although splinting and poultice have been used for cases where no serious vascular or nerve damage was involved. However, nowadays new tools are created to improve the recovery and ease the work of the therapist.

1.1 Wrist Anatomy

Understanding wrist anatomy is crucial for treatment and rehabilitation. It includes bone and ligament classification, innervation, blood supply, skin and muscles. For example, surface anatomy of the wrist is useful for the anatomist to look for pathological conditions and to determine points of instability, swelling, and maximum tenderness and correlate these findings with underlying structures to reduce the list of potential diagnoses.

The wrist is composed by eight bones which can be classified into distal and proximal. Distal bones are trapezium, trapezoid, capitate and hamate; proximal bones are scaphoid, lunate, triquetrum and pisiform. Distal radius and ulna are also important bones when dealing with the wrist (fig. 1.1). Next, a brief description of each carpal bone is given:

- **Scaphoid** is the largest bone of the proximal row and it is an important link between the distal and the proximal row.

- **Lunate** is considered by many autors as the keystone bone of the carpus. Depending on the angle between its scaphoid and radial faces, three types of lunate are defined: type I, type II, and type III [1] (fig.1.2). Lunate morphology may affect

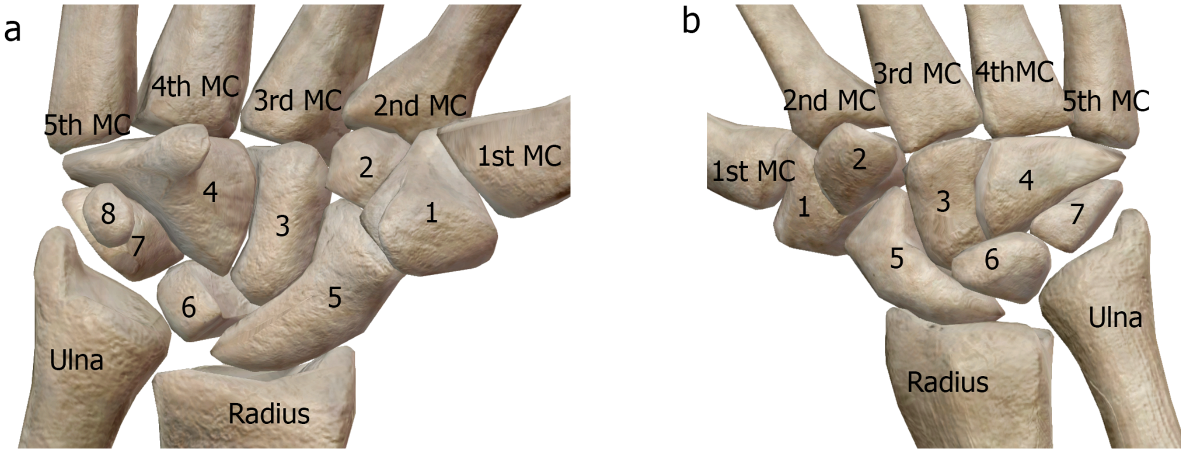


Figure 1.1: Wrist Bones of the right hand. a-palmar view, b-dorsal view, from 1 to 8: trapezium, trapezoid, capitate, hamate, scaphoid, lunate, triquetrum, and pisiform. Five metacarpals (MC) are partially shown.

the severity of Kienböck disease at the time of initial presentation, it can also have implications within the treatment,and may affect other carpal pathologies [14].

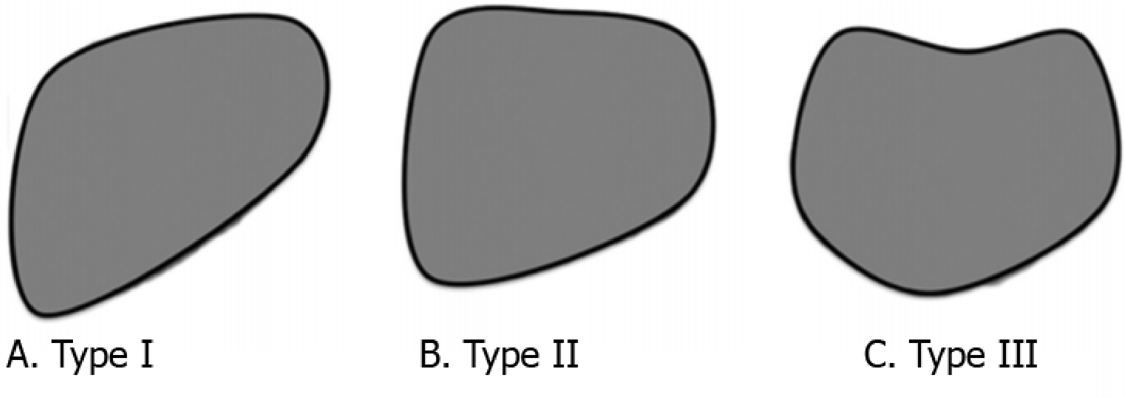


Figure 1.2: Shapes of lunate identified by Antuno-Zapico Adapted from [1]

- **Triquetrum** is a well vascularized bone which receives multiple ligamentous insertions
- **Pisiform** serves as an attachment for tendons and ligaments. Even if it is considered as a carpal bone, it functions as a sesamoid bone as it acts as a pulley that provides a smooth surface for the flexor carpi ulnaris tendon to glide over.
- **Trapezium** is the most mobile bone of the distal row, and it is firmly bound to the trapezoid.
- **Trapezoid** is the smallest bone of the distal carpal row, and because of the rarity

of injuries related there is not a standard treatment for it, however, a wide range of treatments are possible, including rest, surgery and casting [15].

- **Hamate** takes part of the carpal arch and is the bone that medially closes the carpal tunnel [1] that is the passageway on the palmar side of the wrist that connects the forearm to the hand [16]

- **Capitate** is placed in the most central position of the wrist, and it is the biggest of the carpal bones, and it is more likely to fracture with the scaphoid if the wrist is injured [17]

- **Distal Radius** is the extreme of the radius that joints the wrist and faces the scaphoid and the lunate (fig. 1.3).

- **Distal Ulna** is made of three parts and articulates with the sigmoid notch of the distal radius, (fig. 1.3).

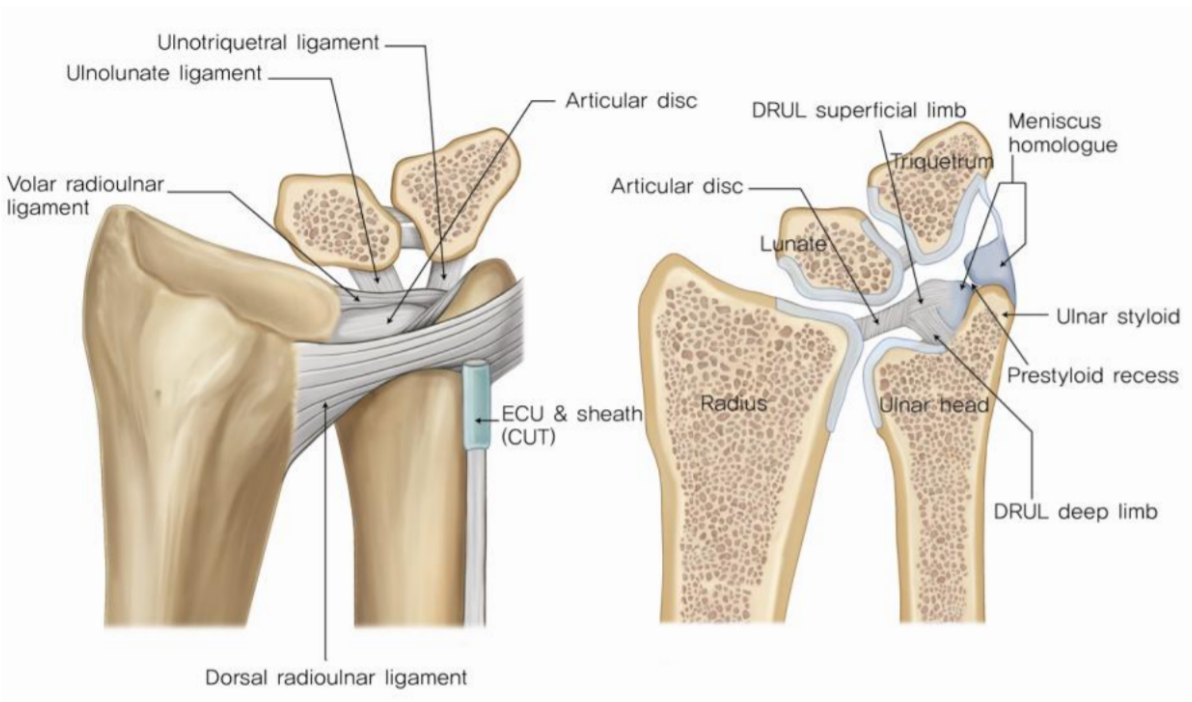


Figure 1.3: Distal Radio Ulnar Joint. Adapted from [2]

1.2 Wrist Biomechanics

Human wrist has two degrees of freedom (DOFs) [18], flexion-extension, adduction-abduction, however pronation-supination motion which also involves the motion of the hand, and may affect it [19–23] , is also mentionend(see figure 1.5).Muscles involved are show in figure 1.4 .

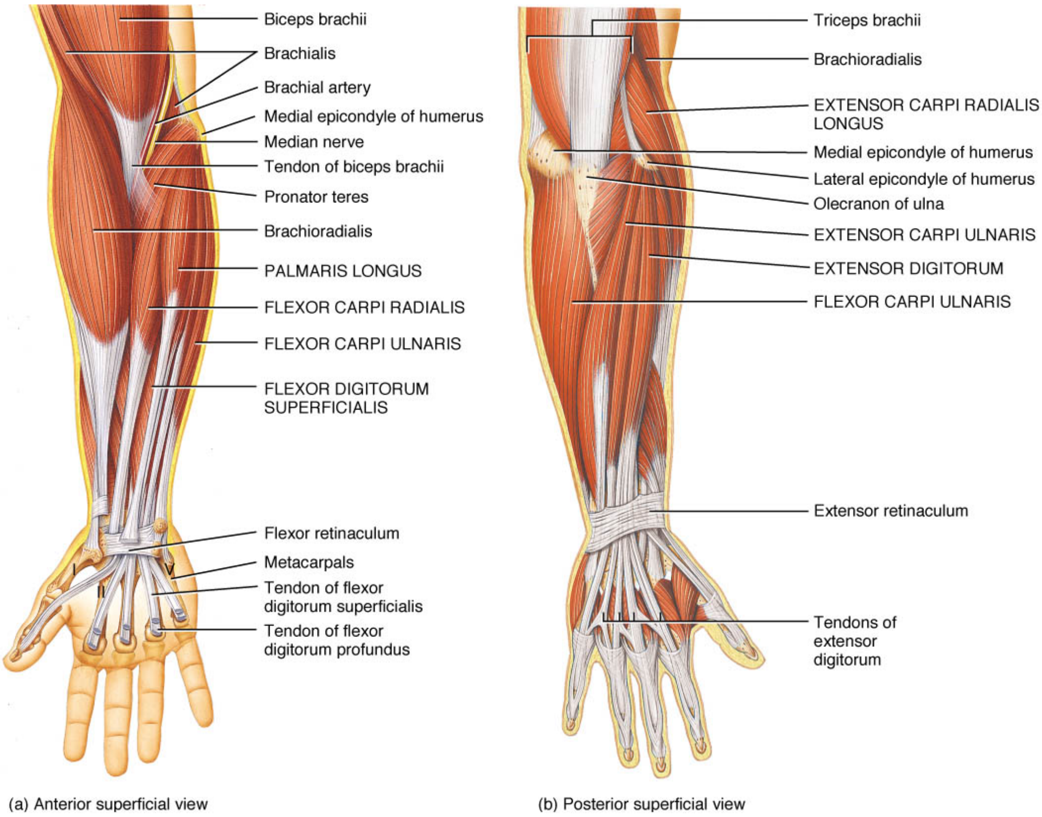


Figure 1.4: Muscle anatomy of the hand and forearm.[3]

- Flexion: The palmar surface of the hand moves towards the anterior section of the forearm.

- Extension: The dorsal surface of the hand moves towards the posterior part of the forearm.

- Ulnar deviation or adduction: The hand moves toward the axis of the body and the ulnar side forms an obtuse angle with the forearm.

- Radial deviation or abduction: The hand moves towards the posterior aspect of the forearm. Range of motion of the above mentioned movements are shown in table

Next movements begin from the elbow, however the wrist in involved because of the interaction of the distal and proximal radioulnar joints:

Movement	Max degree of motion
Flexion	60
Extension	54
Abduction	40
Aduction	17

Table 1.1: Range of motion of the wrist Human wrist degrees of freedom. Adapted from ref. [13]

- Pronation: It corresponds to a forearm rotation allowing the hand to be positioned with the back facing up.

- Supination: It corresponds to a forearm rotation allowing the hand to be positioned with the back facing down.

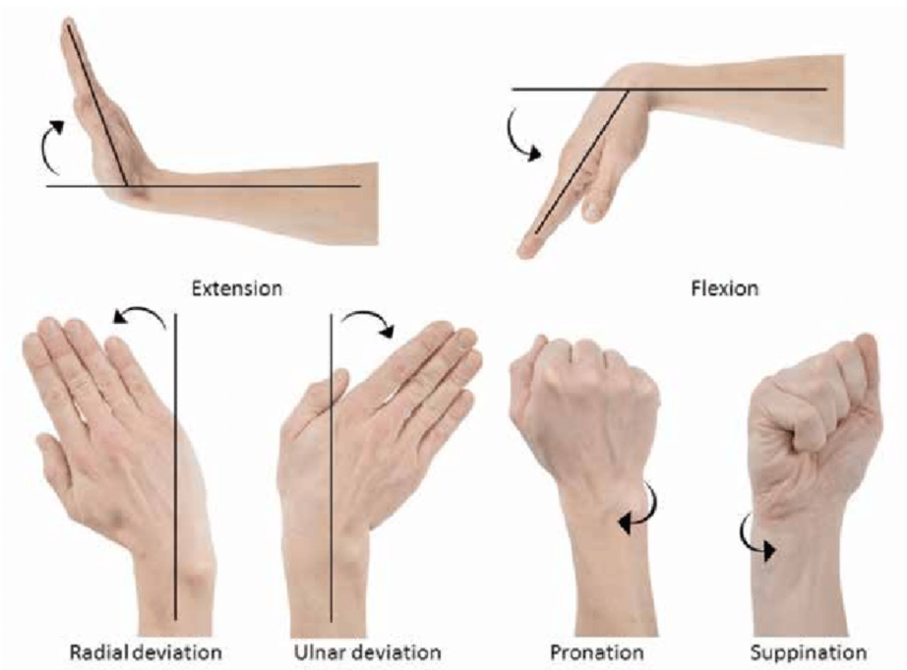


Figure 1.5: Human wrist degrees of freedom. Adapted from ref. [4]

1.3 Physical Rehabilitation

Physical rehabilitation, a speciality of the health sector, is aimed to restore or recover functional ability and quality of life to patients who have any type of physical impairment or disabilities which may affect any part of the motor system.

1.3.1 Wrist Rehabilitation

Hand injuries are the most common bodily injuries, which treatment is long lasting, and also a big expense for the community [24]. Wrist sports injuries are common in every level of competition. It has been estimated that a fourth part of all the sports injuries occur in the wrist. The athlete's hand is exposed to contact and the hand is frequently used to deviate and absorbs the impact on the opponents, balls, or any object within the sports space. Those injures mean 20% of the visits of patients to hospitals and may become a big economic cost. Wrist injuries should be priority in attention and management in physical therapy research and technology, and in trauma care in general. Advances within this area would mean great saves for the health system and to the society. Commonly, wrist pain is caused by sprains or fractures, however the wrist pain can also be caused by long term problems, as repetitive stress, arthritis or carpal tunnel syndrome [25].

Injuries to the hand and wrist represent approximately 20 % of patient visits to the emergency department and can pose a significant financial burden. Hand and wrist injuries are not only a substantial part of all emergency services. But also represent a considerable financial burden, health and productivity costs. Hand and wrist injuries should be a priority area for research in trauma care, and further research could help reduce the cost of these injuries, both to the health care system and to society. [26].

Wrist problems are commonly treated with exercises aimed to improve range of motion and/or any drug to reduce the pain if applicable. From mechanical to optical devices are addressed to manage wrist and hand problems in general [27–35].

1.4 Human motion analysis

The aim of human movement analysis (HMA) is to quantify the function and structure of the skeletal muscle system during the performance of a specific task [36]. HMA has different applications, including physical rehabilitation, sports training in movement monitoring and analysis, for example, to implement different exercises to improve treatment or training. Within this, in Ecuador there has been little relevance given to biomedical engineering, and in national development in the area of biomechanics as well. This can be evidenced with the lack or scarcity of study centers and degree, or related postgraduate programs. It can also be evidenced with a health system that is mainly dependent on medical devices from abroad and at generally poorly accessible costs.

In physical rehabilitation, it is important to implement tools that facilitate the monitoring of the patient, as well as the way in which the patient is involved with the treatment. Different tools have been used for the application of monitoring human movement. Among them optical, magnetic, electrical, mechanical sensors, including wearable devices and recently the use of artificial intelligence and machine learning to improve the analysis [37–40]. As mentioned in section 1.7, different types of sensors can be used for HMA through videogames. However, this work is only focused on information obtained through inertial sensors.

1.5 Inertial Sensors

Inertial sensors in inertial measurement units (IMUs) are devices intended to measure linear acceleration (accelerometers) or angular velocities (gyroscopes). Also, they should not obstruct or interfere with natural movements. There are several types or commercial IMUs, that may include accelerometer, gyroscope, magnetometers [41].
IMUs have several applications in health, rehabilitation, sports, serious games, among others (see table 1.2). It can also be used with other sensors to be embedded within wearable systems. Those systems may have many applications within health, among them fall detection and posture monitoring for elderly, patients with Parkinson's disease, and assisted Living for elderly/patients with chronic disabilities/impaired people [42].

Advances in technology allow the creation of smaller and cheaper sensors improve clinical practice and rehabilitation treatments, musculoskeletal or neurologic conditions [43].

1.5.1 Accelerometers

Accelerometers are devices used to measure the vibration or motion of a structure and is based in the displacement of an inertial mass under the effect of an external force or acceleration(fig. 1.7). There are some types, among them: capacitive, piezoresistive and piezoelectric accelerometers. [6, 65]. Main specifications of accelerometers include:
Full-scale range (commonly given by G where G=9.81 m/s2) indicates the full scope of the measurement range.

Application	Example
Rehabilitation	Online tracking of the lower body joint angles using IMUs for gait rehabilitation [44]. Development of an upper limb rehabilitation system using inertial movement units and kinect device [45]. Design, development and control of a tendon-actuated exoskeleton for wrist rehabilitation and training [46]. Development of a low-cost virtual reality-based smart glove for rehabilitation [47]. Gait rehabilitation monitor [48]. Wearable and IoT technologies application for physical rehabilitation [49].
Sports	Advancing Applications of IMUs in Sports Training and Biomechanics [50]. Inertial measurement of sports motion [51]. Live-feedback from the IMUs: animated 3D visualization for everyday-exercising [52]. Reliable jump detection for snow sports with low-cost MEMS inertial sensors [53]. Wearable Sensor Validation of Sports-Related Movements for the Lower Extremity and Trunk [54].
Serious games	Hand Gesture Sequence Recognition Using Inertial Motion Units (IMUs) [55]. Wearable human computer interface for control within immersive VAMR gaming environments using data glove and hand gestures [56]. Cost-effective (gaming) motion and balance devices for functional assessment: need or hype? [57]. NUI therapeutic serious games with metrics validation based on wearable devices [58]. Wearable motion capture for 3D games[59]. Cognitive and functional rehabilitation using serious games and a system of systems approach [60].
Other	Features of Acceleration and Angular Velocity Using Thigh IMUs during Walking in Water [61]. Construction equipment activity recognition from IMUs mounted on articulated implements and supervised classification [62]. Stationary Exercise Classification using IMUs and Deep Learning [63]. Evaluation of Smartphone IMUs for Small Mobile Search and Rescue Robots [64].

Table 1.2: Examples of Inertial Measurement Units in human motion research

Sensitivity describes the output voltage generated by a certain force, measured in "g", where g =9.8 $\frac{m}{s^2}$.

Resolution is the acceleration levels or bins measurable, it is obtained from the number of bits of resolution(r) with 2^r structure , where the resolution in acceleration units (au) is obtained by calculating $\frac{range of measurement(au)}{resolution(bins).}$.For example, in a 16-bit resolution system with a range of (-100g,100g) the resolution in au would be:

$2^{16} = 65536$,

resolution(au) $= \frac{200g}{65536} = 0.003$g (resolution)

Bandwidth indicates how sensors respond at different frequencies.

Cross-axis sensitivity refers to the effect that the acceleration on one axis may affect the readings for other axes. Each axis has two cross axis sensitivities:

$X : S_{XY}, S_{XZ}$

$Y : S_{YZ}, S_{YX}$

$Z : S_{XY}, S_{ZX}$

Capacitive

The relative position motion of the boards of a microcapacitor is modified when they are subject of motion. This motion causes a change in the capacitance. Those types of accelerometers are based in the measurements obtained from the capacitors(see an example in fig.1.6).

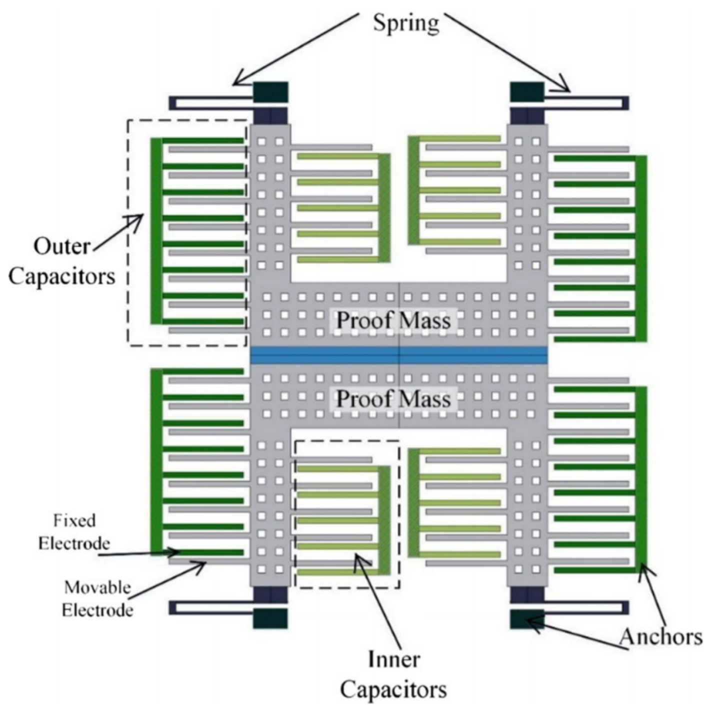


Figure 1.6: Example of capacitive accelerometer proposed by Keshavarzi and Yavand [5]

Piezoresistive

This type of accelerometer converts the changes in resistance of piezoresisitve materials to measure the changes in voltage.

Piezoelectric

A piezoelectric accelerometer is based on the property of piezoelectric materials which converts to electricity any force or acceleration on it.

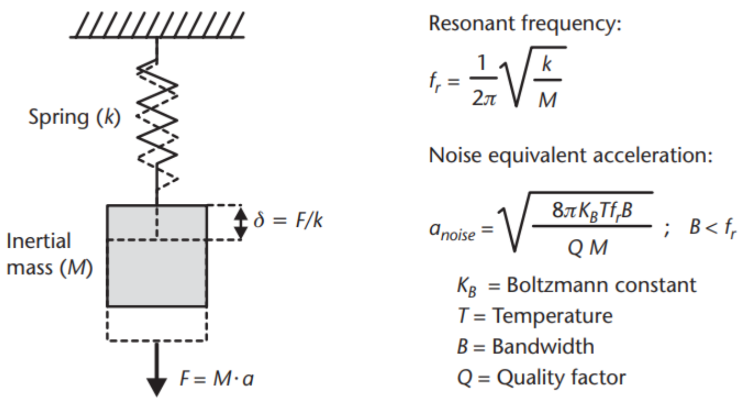


Figure 1.7: Basic structure of an accelerometer consisting of an inertial mass from a spring [6]

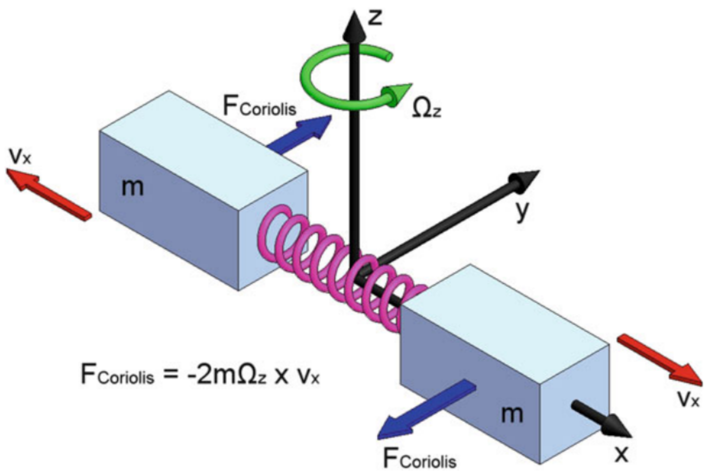


Figure 1.8: Principle of operation for MEMS vibrating gyroscope. There, V_x and Ω_z represent velocity and angular rotation correspondingly. Adapted from ref. [7]

1.5.2 Gyroscope

Gyroscopes measure the angular rotation around a fixed axis with respect to an inertial space. There are three types of gyros: spinning mass, optical and vibrating. Important parameters should be regarded when referring to gyroscopes, such as scale factor, input and output range, bias, resolution, full range, dead band an dynamic range. Scale factor is associated with the sensitivity, as it gives the proportion between the sensor output and the variation in angular velocity. Input refers to the range of input values when it matches a specified precision. Output range is the product of the scale factor with the input range. Bias corresponds to the average of the gyros output when it has no correlation with the input rotation over a period of time. The smallest angular speed that can be detected by the gyroscope is known as resolution. Dead band corresponds to the range of rates where the sensor has no longer sensitivity as it reduces to zero. The dynamic range is the relationship between the resolution and the full range which is the algebraic difference between the upper and lower values from the input range [66–68],

1.6 Rotations

In the development of computer graphics transformations (scale, translation and rotation) are essential tools to modify the position and orientation of an object or virtual camera. Among transformations, rotation is the most problematic; however different approaches are taken to proceed with rotation transformations, such as Rotation matrix, Euler angles, Euler–Rodrigues parameterisation, quaternions and multivectors. Euler angles and quaternions will be highlighted

1.6.1 Rotation Matrix

The rotation matrix is an orthogonal 3×3 matrix which conserves vector length after applying the linear transformation in $\mathbb{R}^3$. It allows us to perform rotations given specific angles in Euler representation (θ, ϕ, ψ) [69].

$$\mathbf{R} = \begin{bmatrix} r1 & r1 & r3 \end{bmatrix}$$
$$= \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

There are three main rotation matrices in $\mathbb{R}^3$ in which one Cartesian coordinate is kept fix as axis of rotation. They are the following:

x : θ ;

$$\mathbf{R}(x, \theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix}$$

y : ϕ

$$\mathbf{R}(y, \phi) = \begin{bmatrix} \cos(\phi) & 0 & \sin(\phi) \\ 0 & 1 & 0 \\ -\sin(\phi) & 0 & \cos(\phi) \end{bmatrix}$$

z : ψ

$$\mathbf{R}(z, \psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

1.6.2 Euler Angles

Euler angles refers to a set of angular coordinates which are used to specify the orientation of an orthogonal reference system mobile, facing other orthogonal reference system that is fixed. Euler angles are ϕ, θ, ψ , which refer to spin (roll), theta (pitch), and precession (yaw) respectively. Any rotation can be described by three successive rotations about linearly independent axes. However, its use may appear the gimbal lock problem.

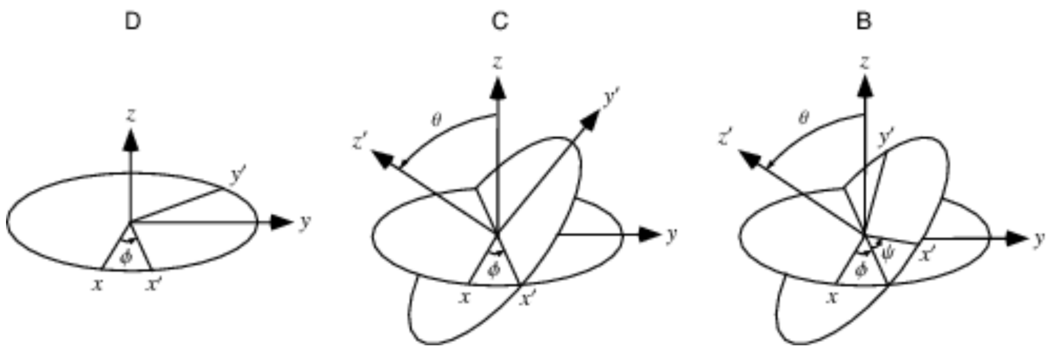


Figure 1.9: Euler Angles for a rotation A that can be written as: A = BCD [8]

Rodrigue's Rotation Formula

It is an algorithm used to rotate a vector in space, it is calculated as follows. First, a vector $\boldsymbol{y} = (0{,}1{,}0)$ is taken as base for the rotation. Next step is to make the cross product $(\boldsymbol{k} \times \boldsymbol{y})$ to get a new vector, $\boldsymbol{s}$, which is perpendicular to vector $\boldsymbol{k}$. Then, to obtain the vector $\boldsymbol{v}$, pointing up and perpendicular to the axis, it is necesary to calculate the cross product $(\boldsymbol{s} \times \boldsymbol{k})$.

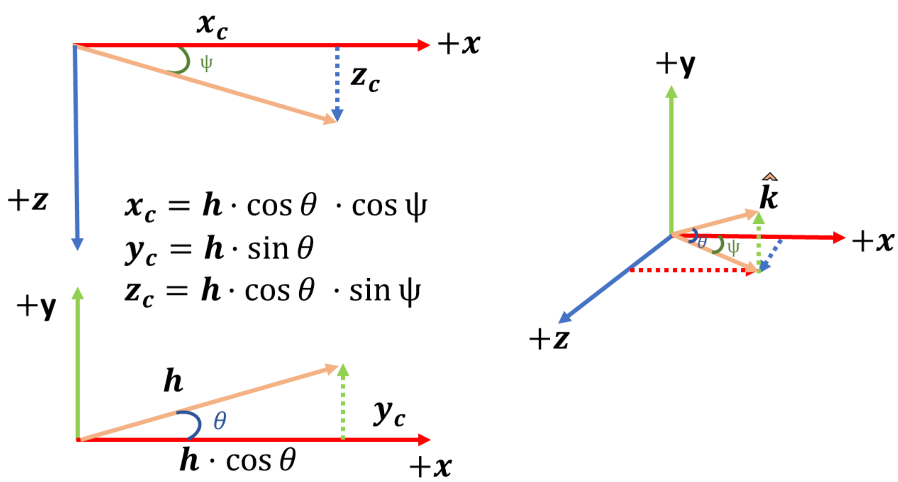


Figure 1.10: Representation of vector $\hat{k}$ and its components. Adapted from [9]

See figure 4.10 to see the plot of vectors $\boldsymbol{k}$, $\boldsymbol{s}$,and $\boldsymbol{v}$, and figure 4.11 to see the location of vector $\hat{k}$ as axis and the vector v as **up** in the object. So, using this equation is possible to move a three-D object using angles and vectors.

Gimbal Lock

Gimbal lock consists in the loss of one degree of freedom in a three dimensional gimbal. It occurs when two of the rotors place in parallel.

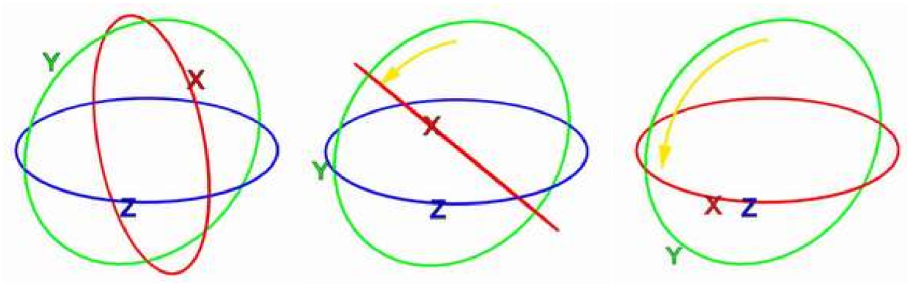


Figure 1.11: Gimbal lock. When the pitch (Y) rotates 90 degrees the roll (X) and yaw (Z) axes become aligned and one degree of freedom is lost. Adapted from [10]

1.6.3 Quaternions

Quaternions (Q) are an extension of real numbers similar to complex numbers. While complex numbers add an imaginary unit i such that: $i^2 = -1$; in quaternions, three imaginary units are added i, j, k to real numbers such that: $i^2 = i^2 = i^2 = ijk = -1$

A quaternion is a number with the following structure :

$Q = q_0 + q_1\hat{i} + q_2\hat{j} + q_3\hat{k}$

$Q = q_0 + \mathbf{q}$

q_0 : real or scalar part

$q_1\hat{i} + q_2\hat{j} + q_3\hat{k}$: imaginary or vectorial part

Quaternions can be applied within differente areas in science and engineering. Those applications include, but not limited to, spacecraft, animation, attitude determination, and dynamics of multibody systems.[70]

1.6.4 Complementary and Kalman Filters

IMUs are devices that cannot give exactly angles, this can be caused because of noise or any error. Noises are all the electrical (or not) undesired signals that are linked to the main signal and may alter it and can be harmful to the final result. The accelerometer is able to measure any angles, however its readings are very noisy and have a certain margin of error.

The accelerometer is also able to capture other than gravity. So, if the IMU is moved without being rotated applying acceleration in the other axis; it will detect it as a change of rotation.

On the other hand, gyroscopes have very precise measurements, but the calculation of the angles produce a little error that accumulates over time causing a meaningful drift of the signal.

With the aim to clean noises and errors, different filters in the form of algorithms are applied. Kalman filter allows to find the error of every measure from the previous measurement, delete it and give a more precise value for the angle. However, it is computationally expensive and complex. Other filter commonly used is the complementary filter, it is precise and it's made under the joining of one high-pass filter for the gyroscope and one low-pass filter for the accelerometer. From this combination next equation is obtained :

$$\theta = 0.98\,[\theta + \theta_{\text{gyroscope}} \cdot \Delta t] + 0.02\,[\theta_{\text{accelerometer}}]$$

where θ represents an angle and the angles from the right side comes from the previous measurement.

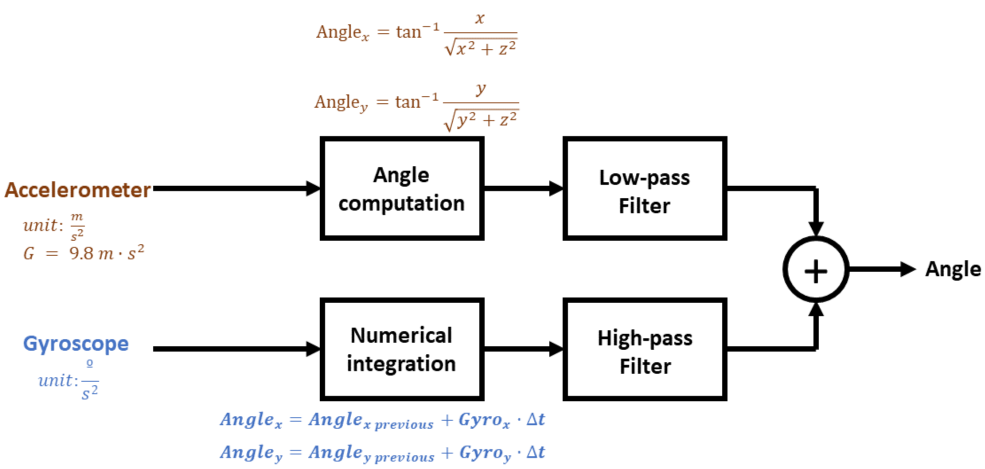


Figure 1.12: Schematics of complementary filters. Adapted from [11]

1.7 Serious Games

Serious games refers to games which aim is not just to entertain, but for other applications, such as learning, health, rehabilitation or training. The use of games with other purposes than entertainment has an historical precedence [71].
On the other hand, a wearable device (WD) is a small computer with the capability to sense, process, store and communicate the information. Watches were the first WD developed in the 16th century , which were purely mechanical. Then, the advances of technology allowed development of electromechanical and electronic watches. Watches were the most known WD until the arrival of mobile phones. Mobile phones allow fast communication and its use rapidly expanded worldwide until nowadays. The co-evolution of electronics and mobile technology and its miniaturization allowed capabilities that are not expected in its classical definition. Nowadays, mobile phones have become smartphones with several applications. Those applications include monitoring, personalized health, sports/fitness, rehabilitation, social communication, lifestyle computing and personal entertaining, and also allow to connect almost anyone almost anywhere, capability that makes possible tracking exercise or monitoring a patient in a hospital.

Also, new trends have modified the way that we play video games (VG). Moreover, they have allowed the study and analysis of new devices with potential for clinical and research applications. Some game controllers have interesting characteristics similar to those used in clinics for motion analysis. Therefore, VG consoles and controllers can be used, and are used for other applications more than just fun, they are already used for motion analysis and rehabilitation monitoring. Many devices use motion analysis using marker based systems, also called optoelectronic devices. Considered the golden standard for the analysis of motion, even if other types of systems are discussed in literature. Those types of systems are composed of several infrared cameras with markers attached to the subjects of study. Then the motion and tracking is studied thanks to the capture of the cameras. Video Games have been tested in different health conditions, with good results within this new trending. The studies within this area are mainly focused on neurologic rehabilitation. In general, results show that VGs rehabilitation therapies are, at least, as good as the traditional treatments. The majority of the patients prefer VG for its rehabilitation; however some prefer the traditional ones. VGs can integrate different movements and so have several advantages such as avoiding boring, monotony, increased motivation, giving daily feedback, and allowing double tasking training. There is little information about the different risks that can be shown within videogames, falls, secondary effects. Many results show that VGs can be integrated in public health systems even if the video games used are not mainly focused for clinical application. A big need of working on game development is present now to improve the current treatments[72].

Computer games have been recognized as great tools for motivation during rehabilitation for at least a decade. Traditional rehabilitation includes exercises that are commonly repetitive, boring and require the supervision of a physiotherapist. New opportunities in rehabilitation arise from the popularity of video games and the development of new sensors, cameras, equilibrium pads, or accelerometers. Even if there is active research within this area, there is a need for many types of video games to be applied in different therapies. Motion analysis systems must proportionate precise measurements and make the game and the analysis behind clinically relevant [73]. Discussing and comparing optic sensors and gloves as VR devices helped in the introduction of a guide for future devices. Those recommendations can refer to technology, ergonomics, appearance and economy. Within development in this technology area, next points should be taken into account:

- Sensor information should be continuous and give reliable information.
- Calibration should not be required
- Wireless communication with the interface allows better flexibility within the treatment and the user comfort..
- Smart devices, as cell phones or computers are almost in every house and should be integrated within serious games.
- Telerehabilitation must be supported, so there is a need for a tool that can be carried by the patient and allow the monitoring from the therapist.

On the ergonomics area, some points should be observed:

- The device must be easy to handle, to be used as much time and in the maximum number of therapies.
- The material of the device should also be user friendly, comfortable and must ensure grip.

- A good design is also desirable to the comfort of the patient.

On the other hand, the appearance of the device also includes the patient desires and should be examined, as well as:

- The device should be able to adapt to different tasks, also can have some additional functional parts.
- The device must be focused on looking for patient entertainment and engagement.
- It should not have a high price, a price under 300$ is recommended.
- Virtual reality glasses offer a wide range of opportunities for future development.
- Fitness bracelets and smartwatches have the possibility of recording physiological measurements. One application is the use to treat stress of a patient during training [74].

Recent technological advancements have enabled the creation of portable, low-cost, and unobtrusive sensors with tremendous potential to alter the clinical practice of rehabilitation. The application of wearable sensors to track movement has emerged as a promising paradigm to enhance the care provided to patients with neurological or musculoskeletal conditions. These sensors enable quantification of motor behavior across disparate patient populations and emerging research shows their potential for identifying motor bio-markers [75–79], differentiating between restitution and compensation motor recovery mechanisms, remote monitoring [61, 80–82], telerehabilitation [83–86], and robotics [87–89]. Moreover, the big data recorded across these applications serve as a pathway to personalized and precision medicine. Several clinical applications are presented across a wide spectrum of conditions that have potential to benefit from wearable sensors, including stroke [90–92], movement disorders [93–95], knee osteoarthritis [96–99], and running injuries [100–102].

Telerehabilitation is an emerging method of delivering rehabilitation services that uses technology to serve clients, clinicians, and systems by minimizing the barriers of distance, time, and cost. The driving force for telerehabilitation has been as an alternative to face-to-face rehabilitation approaches to reduce costs, increase geographic accessibility, or act as a mechanism to extend limited resources. Most of the literature on telerehabilitation targets these needs, and justifies the use of telerehabilitation by attempts to empirically equate remote services delivered via telerehabilitation to face-to-face services. The potential to enhance outcomes beyond what may result from face-to-face interventions by enabling naturalistic, in vivo interventions, is another reason to work in this area. There is considerable support for the value of interventions delivered in the natural environment, ranging from addressing efficacy concerns by pointing out problems of generalization, to increasing patient participation, including environmental context in rehabilitation, and increasing patient satisfaction. These potential outcomes are consistent with promoting quality of life. Further clinical and research exploration should explore telerehabilitation as a tool for the delivery of rehabilitation services in vivo [103].

A major goal of physical medicine and rehabilitation is the recovery of function after an injury or the underlying medical condition that has caused impairment in one's daily functioning. The rehabilitation process involves a complex interplay of many factors that influence how well a person benefits from medical rehabilitation. There is evidence that for patients to maximize rehabilitation benefits, they must be actively involved or engaged in the process [104].

Effective stroke rehabilitation must be early, intensive and repetitive, which can lead to problems with patient motivation and engagement. The design of VGs, often associated with good user engagement, may offer insights into how more effective systems for stroke rehabilitation can be developed. Some game design principles for upper limb stroke rehabilitation and present several games developed using these principles [105–107]. The games use low-cost video-capture technology which may make them suitable for deployment at home. Results from evaluating the games with both healthy subjects and people with stroke in their home are encouraging [108].

Engagement appeared to be conceptualized in two interconnected ways: as a gradual process of connection between the healthcare provider and patient; and as an internal state, which may be accompanied by observable behaviors indicating engagement. While engagement is commonly considered a patient behavior, the review findings suggest clinicians play a pivotal role in patient engagement. Implications for Rehabilitation Engagement appears to be a multi-dimensional construct, comprising both a co-constructed process and a patient state. Conceptualizing engagement as a co-constructed process may help clinicians be more aware of their role in patient engagement and sees the responsibility to engage shift from the patient to the therapeutic dyad. The ability of the therapist to engage the patient into the therapeutic process is reflected on how the clinician is working and whether different ways of working may be beneficial .Viewing engagement as a co-constructed concept provides a rationale for shifting the responsibility to engage from the patient to the therapeutic dyad. Challenges in engagement may be seen as a prompt to critically reflect on what the clinician is doing and how the two parties are working together and consider new ways of working in order to promote engagement in rehabilitation [109].

Patient nonadherence with therapy is a major barrier to rehabilitation. Recovery is often limited and requires prolonged, intensive rehabilitation that is time-consuming, expensive, and difficult. Evidence for the potential use of VGs in rehabilitation with respect to the behavioral, physiological, and motivational effects of gameplay is present. VG as a good tool on motor learning and their potential to increase patient engagement with therapy, particularly commercial games that can be interfaced with adapted control systems.
A novel approach is taken to integrate research across game design, motor learning, neurophysiology changes, and rehabilitation science to provide criteria by which therapists can assist patients in choosing games appropriate for rehabilitation. Research suggests that VGs are beneficial for cognitive and motor skill learning in both rehabilitation science and experimental studies with healthy subjects. Physiological data suggest that gameplay can induce neuroplastic reorganization that leads to long-term retention and transfer of skill; however, more clinical research in this area is needed. There is interdisciplinary evidence suggesting that key factors in game design, including choice, reward, and goals, lead to increased motivation and engagement. VG play could be an effective supplement to traditional therapy. Motion controllers can be used to practice rehabilitation-relevant movements, and well-designed game mechanics can augment patient engagement and motivation in rehabilitation. It is recommended future research and development exploring rehabilitation-relevant motions to control games and increase time in therapy through gameplay [110].

Ambar et al. proposed a wrist rehabilitation device that incorporates an interactive computer game so that patients can use it at home without assistance. The main structure of the device is developed using a 3D printer. The device is connected to a computer, where the device provides exercises for the wrist, as the user completes a computer game which requires moving a ball to four target positions. Data from an InvenSense MPU-6050 accelerometer is use to measure wrist movements. The accelerometer values are read and used to control a mouse cursor for the computer game. The pattern of wrist movements can be recorded periodically and displayed back as sample run for analysis purposes. In this paper, the usefulness of the proposed system is demonstrated through preliminary experiment of a subject using the device to complete a wrist exercise task based on the developed computer game. The result shows the usefulness of the proposed system [111].

Another example combines serious gaming, healthcare, and smartphones to create a digital tool for wrist rehabilitation, namely Droid Glove. Based on the new Android open source platform for mobile phones, it has the innovative advantage of allowing ubiquitous game therapy, with also the possibility for the doctor to verify the exercises done at home by the patient. Network support could be introduced to centralize data collection or to create a public leaderboard to induce patients in improving the quality of their exercise, then improving rehabilitation and engagement [112].

As shown by Afyouni et al. who designed an adaptive gamification approach, it is possible to assess and track the rehabilitation of the patient through the use of deep learning to follow the evolution of data over time and improve the range of motion of the wrist. Also, as seen with the work of other authors, machine learning, neural networks and broadly artificial intelligence can be used for rehabilitation [113–119].

1.8 Arduino

Arduino is a company of open hardware and software development. They assemble platforms based on open hardware which includes a microcontroller and female headers for sensors or other devices connection. Arduino was created in 2005, and since then it has been used in several projects related with biomedical and biomechanical engineering [120–128], among them, the wrist have become a relevant issue for research and development [129–148].

As mentioned, arduino is able to connect and set up different types of sensors. Inertial Sensors (see section 1.5) can be used to measure wrist motion, in this work, MPU6050 IMUs are used. Remember that IMUs are electronic devices used to measure obtained attitude, speed , and position through the use of accelerometers, gyroscopes, and sometimes magnetometers. MPU6050 were chosen because of its price and availability, however there are several types of sensors that can be used with similar purposes [149], also for the identification of diseases related with motion [150]. Although Arduino allows the preprocessing of the data collected from the sensors, it is possible to use other platforms to ease the work with and build different applications. In this case, I propose the use of Python programming language to process and manage the data.

I2C

Inter-Integrated Circuit (I2C), communication protocol, has two type of connection towards the connection of sensors and devices, SCL (clock signal) and SDA (data transfer). Each I2C device has a unique address. Some addresses are fixed while other devices allow the configuration of its address by setting pins high or low, or by means of any command [151].

1.9 Python

Python is an interpreted, high-level, general-purpose programming language. I chose this language it in this project because it is simplified and fast, also because its community offers several open-source tools for the development of projects. Within the community, there are several packages or libraries which ease the process of development to work with Python. Also, the community allow to address issues from several areas of knowledge.

Among other libraries used, next are highlighted for the system developed here:

Pyserial

Pyserial library allows the communication to the Arduino system, and provides access to the serial ports to obtain the input data provided to the system by sensors or other devices [152].

Tkinter

This module is considered a standard for the graphical user interface (GUI) for Python and is the one that comes by default with the installation for Microsoft Windows [153].

VPython

It is a module used to create objects in a 3D space and display them in a window. It allows visualizations that can be used commercially for research or education due to the ease to show simple physics simulations [154]. It has been used for projects related with rehabilitation [99, 155–157].

Sqlite3

As the project is oriented to be a tool for physical rehabilitation therapists, it was necessary to store digitally the patient's information within a database for further analysis. Sqlite3 library gives the platform to store and manage the data obtained for different patients and also has been shown as a useful tool to use in telerehabilitation [158–160]

Chapter 2

Problem Statement

According to Maclean and Pound, three main causes relate physical rehabilitation and motivation of the patients: First variable is, internal dispositions of the patients linked with their personality. Second cause is related to social factors, economy, or relationships that surround the patient. Finally and third aspect related with motivation of the patient is the quality and behavior of the therapist [161]. Worldwide, there are several cases of people who have any type of motor disability, and require rehabilitation or almost permanent aid. Main causes of disabilities are disease or accidents. "Grupo de Investigación en Ingeniería Biomédica de la Universidad Politécnica Salesiana" is currently in Ecuador one research group oriented to work with tools and investigation oriented to face biomechanical problems through engineering [162]. In addition, our national reality manifests a deficiency in physical rehabilitation services, as well as in the technological tools availability,and the adherence to treatments, either due to lack of resources or distance from the rehabilitation center [163, 164]. Although it is possible to find research in Ecuador related with the use of IMUs in rehabilitation [165–169], there is not any project which includes software and the use of sensors oriented to the use of the therapists in physical rehabilitation to ease their work, and oriented to improve patient engagement and data storage. Hence, a project oriented to face those issues is proposed within this work.

Chapter 3

General and specific objectives

3.1 General Objective

- To design and develop a system to measure, store and manage data obtained from inertial sensors oriented towards the use for physical therapy.

3.2 Specific Objectives

- To validate the accuracy of the device
- To design and implement a low cost sensor system to collect motion data of the wrist.
- To implement an algorithm in order to control and manage the data.
- To build a database with the input data from the user and the data from the sensors.

Chapter 4

Methodology

Information about different systems and needs within physical rehabilitation was provided by different therapists nationwide, finding that they may need a tool to manage and measure range of motion as well as engage the patients in therapies.

4.1 Hardware development

To develop the system, information from different sources were gathered to evaluate similar projects. [12, 170, 171]. Initially, the idea was to emulate the system displayed in 4.1, however, the BNO055 sensors used in the project mentioned were not available in the country. BNO055 were bougth from Mouser electronics, and arrived shortly before the pandemics, so they are left for further work. To solve this issue, national available inertial sensors,two MPU-6050 inertial sensors, were used and a micro-controller type Arduino Nano was acquired for the implementation (see figure 4.2).

Figure 4.1: MotioSuit OpenSource system developed by Álvaro Ferrán. Adapted from [12]

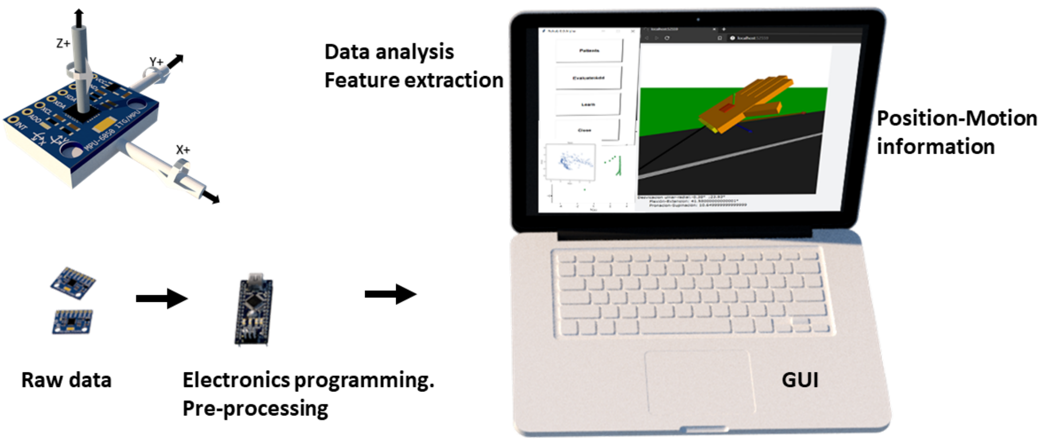


Figure 4.2: Schematics of the project. Prepared by the author.

To test the system, a simple design was made, (see figure 4.3). It was made using a 3D modelling computer software, Sketchup (Trimble), and vRay plug-in to render the image.

The connection of the sensors with the type Arduino microcontroller to get both addresses (0x68, and 0x69) for the sensors is shown in figure 4.4

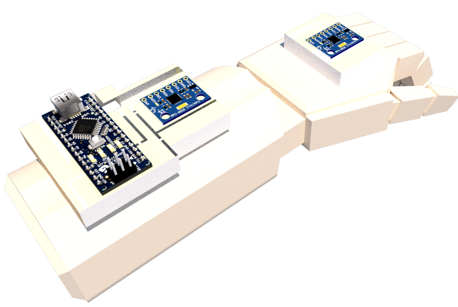


Figure 4.3: Prototype design for the system for data collection. Prepared by the author.

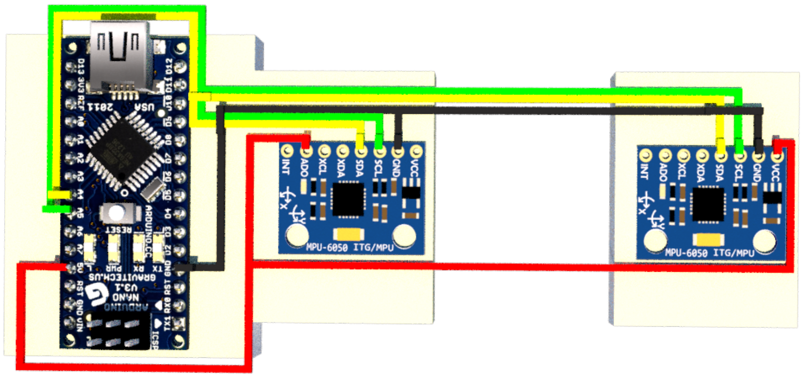


Figure 4.4: Schematics of the sensors connection

4.2 Software development

4.2.1 Arduino

Data acquisition and preprocessing was possible using Arduino IDE in C++ programming language. Information provided within this part of the project are the sensor data transformed into Euler Angles with the MPU-6050 sensors. For future work, with BNO055 sensors, the motion of in the animation will be improved with the use of better quality data coming from those sensors, and that can be read direclty as quaternions.

Code to retrieve and preprocess the information of the sensors begins with the call of the Wire library for Arduino,

```
#include <Wire.h>
```

then is used the **#define** *constantName value* component, which allows to declare constants before the program is compiled, it is used to declare the IMUs addresses and conversion rate constants

```
#define MPU 0x68
#define MPU2 0x69
#define A_R 16384.0
#define G_R 131.0
#define RAD_A_DEG = 57.295779
```

A_R, and **G_R** constants are based on the sensors sensitivity selected by default, with ±250° /s for the gyroscope, and $\pm 2g$ for the accelerometer, that is to say, as the sensor

Accelerometer		Gyroscope	
Full-scale range(+-)	Sensitivity	Full-scale range(+-)	Sensitivity
2g	16384	250°/s	131
4g	8192	500°/s	65.5
8g	4096	1000°/s	32.8
16g	2048	2000°/s	16.4

Table 4.1: Available options to read data

uses a 16 bit analog digital converters for digitizing thee gyroscope and accelerometer outputs, it will have $2^{16} = 65536$ units for measurement, but, as the numbers have positive and negative values, it can be finally written as ±32768, of which it is possible to obtain the conversion rates to calculate the angles (see table). Also (see full code here*), the other variables used in the code are declared.

The angles were obtained from the accelerometer data as follows:

```
Acc[1] = atan(-1 * (AcX / A_R) / sqrt(pow((AcY / A_R), 2)
           + pow((AcZ / A_R), 2))) * RAD_TO_DEG;
Acc[0] = atan((AcY / A_R) / sqrt(pow((AcX / A_R), 2)
           + pow((AcZ / A_R), 2))) * RAD_TO_DEG;
```

The data from the gyroscope were also converted:

```
Gy[0] = GyX / G_R; //Similar for the other inputs in "y" and
    "z"
```

On the other hand, to obtain more accurate angles using both source, accelerometer and gyroscope, a complementary filter was employed:

```
Angle[0] = 0.7 * (Angle[0] + Gy[0] * 0.010) + 0.3 * Acc[0];
```

Finally, values are added to a type string variable which is printed to further be read with the Python Algorithm.

```
valores = String(Angle[0]) + "␣,␣" + String(Angle[1]) + "␣,␣"
   + String(Angle[2])  + "␣,␣" + String(Angle2[0]) + "␣,␣" +
   String(Angle2[1]) +"␣,␣" + String(Angle2[2]);
Serial.flush();
Serial.println(valores);
```

*Code available in GitHub

4.2.2 Python

Visual Studio Code, a free source-code editor was used to write the code in Python Language. Within Python environment, PySerial library was used to bring the values printed by the Arduino Nano micro-controller. Graphical User interface was written with the libraries Tkinter for different windows of the application (windows from the flowchart in figure 4.5), except for the 3D application window which uses the default web explorer of the computer to display it and is written using VPython library (see figure 4.9). SQlite3 library was used to store the data and build the databases with the list of patients and the individual patient databases (*.db files). Matplotlib was used to plot the data recorded for the analysis shown in figures 5.1,5.2,5.3, 5.4,and **??**. Finally, Pandas, and Sklearn libraries were used to the calculate the PCA for further analysis respectively. All libraries mentioned were installed using **pip** package manager

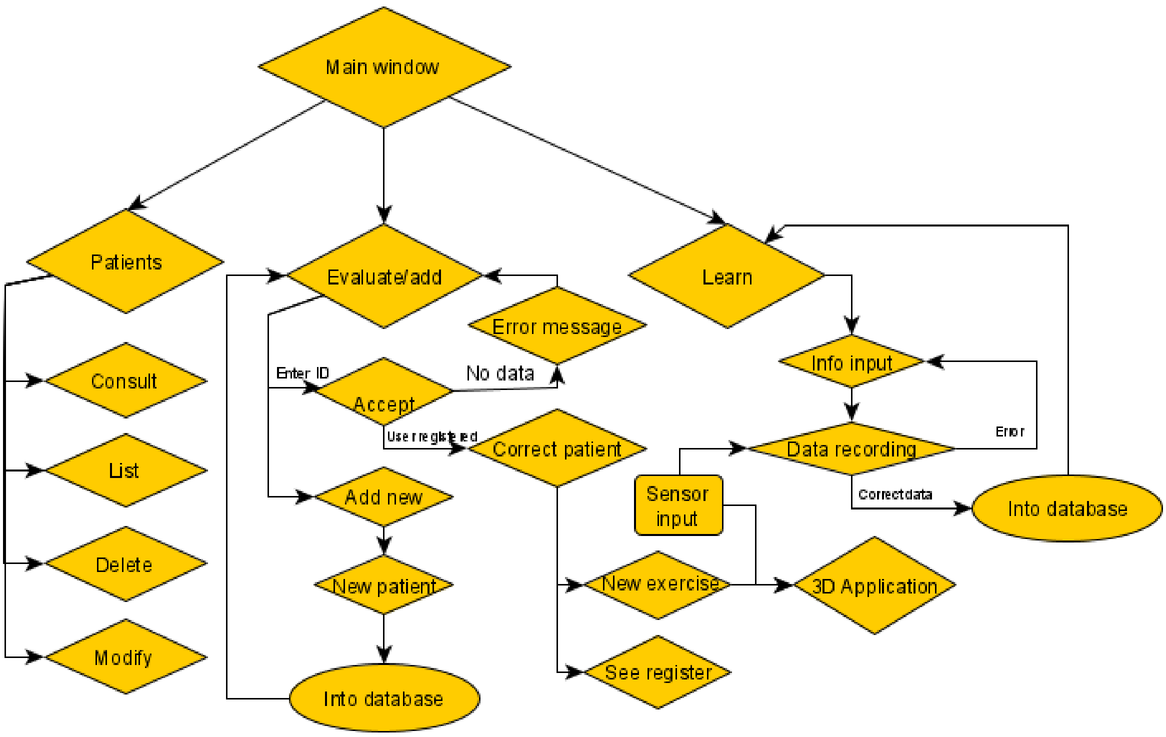


Figure 4.5: Flowchart of the system working

Pip

Pip, package installer for Python was used to load the libraries use in this project.

Pyserial

It is a package which opens the access to the serial ports, see figure 4.6 .

```
arduino = serial.Serial('com13', 115200) #Set the variable
                                         #for the connection
                                         #COM# port can be checked
                                         #when loading the code
                                         #for the arduino
                                         micro-controller
LineArdu = arduino.readline() #Reads line by line of the
                              #input of the port, in this
                              #case the angles printed.
LineArdu = LineArdu.decode('utf-8') #
data = LineArdu.split(',') #Split the line read and make the
                           #variable data which is a list
                           #containing the angles measured
                           #for further use
```

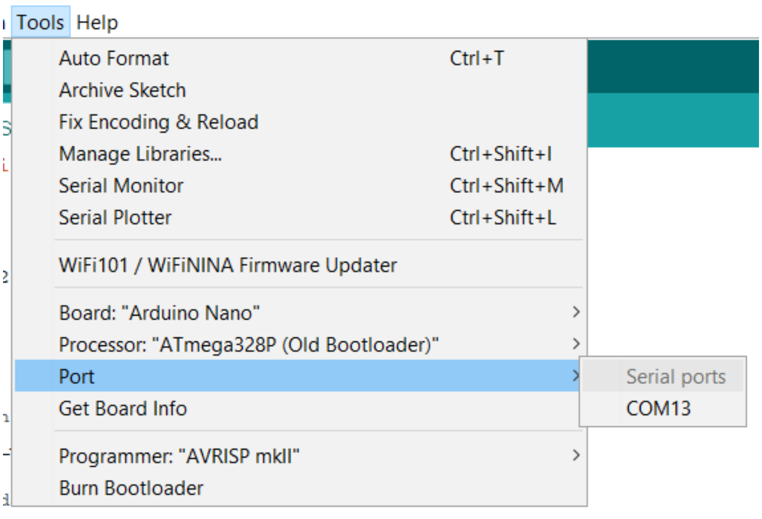


Figure 4.6: Port information in Arduino IDE

.

Tkinter

Graphical user interface was programmed using Python programming language with Tkinter library. Next is shown the syntax for geometry and making of the windows, then the use of the different tkinter widgets used within this project.

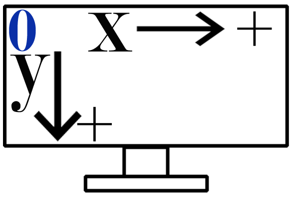


Figure 4.7: Position of pixels in Tkinter

A class was declared for each of the windows in the application, as well as for the database and directories creation, next is shown briefly an example for the main window.

```
class Main:
    def __init__(self):
        self.main()
    def main(self)
        #[...]
```

Tkinter allows to place the window created in any specific pixels of the screen, see reference for geometry in figure 4.7, other than the position, this library provides options to manage other options for the creation of the window, the title, background color

```
self.root = tk.Tk() #Creates the main window
self.root.title("Rehab 0.0 Alpha") #Names the window
self.root.configure(bg = "#ffffff") #Set the background color,
                                     #In this case using HTML
                                     color coding
self.root.geometry("+10+40") #Places the window at pixel
                             "X" =10, and "Y"=40
```

The placement of widgets * in tkinter works as follows:

```
self.NAMEOFTHEWIDGET = tk.TYPEOFWIDGET(self.NAMEOFTHEWINDOW,
                          text= "TEXTINTHEWIDGET",
                         bg='#ffffff',
                         *,
                         command = FUNCTIONCOMMAND,
```

*Widget: One of many small computer programs that make up what you see on a computer screen, and that allow you to take particular actions.(Cambridge Dictionaire)

```
                    height = 1,
                    width = 1, [...])
# *Depending of the type of widget it have different
#options, but with similar structure
self.NAMEOFTHEWIDGET.grid(row=n, column=m) #Grid method places
                                             #the widget sorting it out
                                             #in relationship with the
                                             #other widgets
```

Main windows are shown in figure 4.8

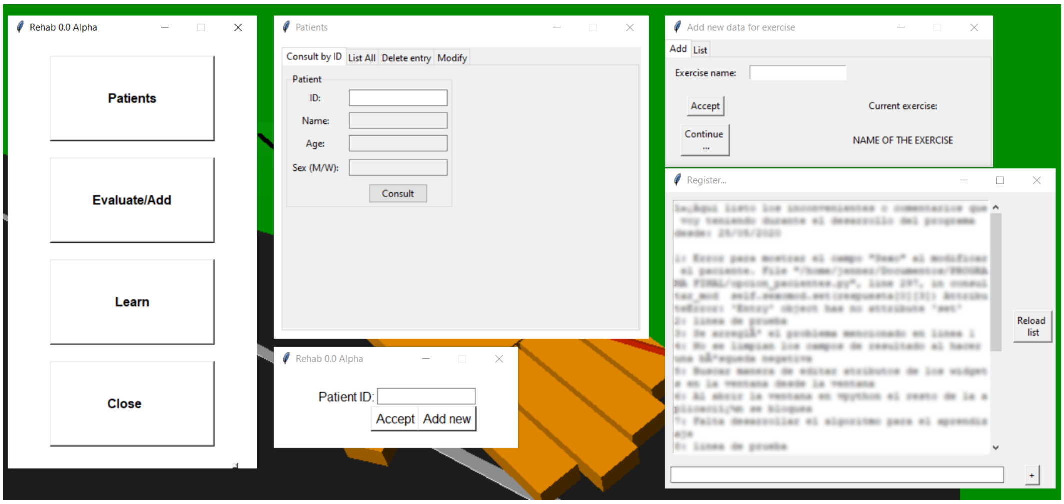


Figure 4.8: Windows that are opened from the main window (root).

VPython

VPython, also known as Visual Python is a tool that allows the illustration of 3D objects for simulations or animations.

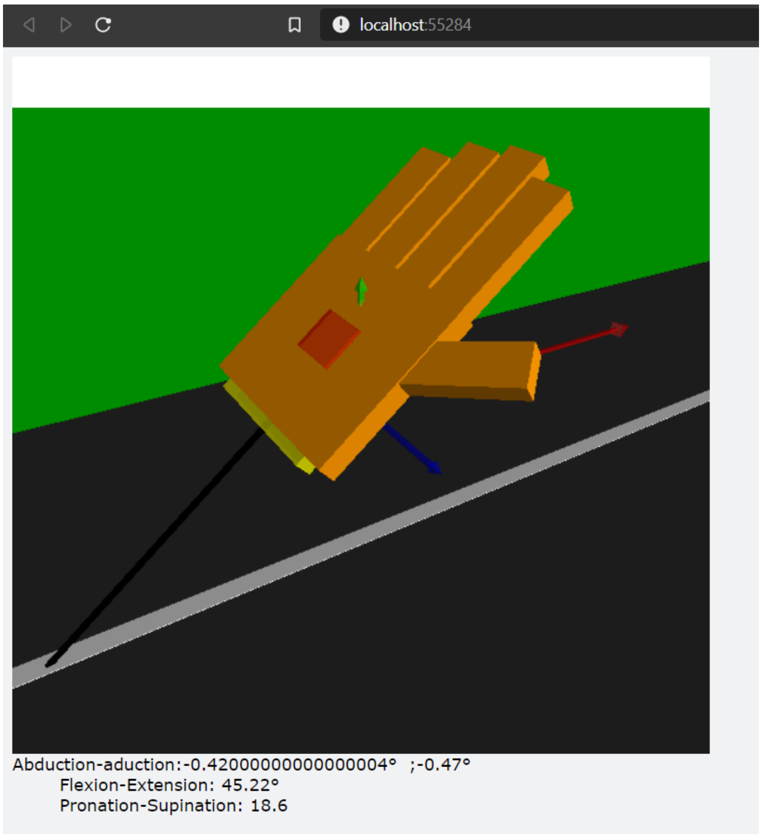


Figure 4.9: Hand in 3D Environment. Prepared by the author.

Data obtained from the sensors were transformed into 3D motion in VPython as follows:

Angles are named after schematics following figures 4.2,4.3, and 4.4 as:

x $=\theta$;

y $=\phi$;

z $=\psi$

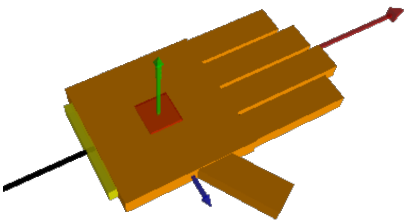


Figure 4.10: "Vectors used in the motion of the hand, k-red, s-blue, v-green

$\hat{\imath}, \hat{j}, \hat{k}$ correspond to the direction of the axis vector of the object (see figure 4.11) The axis vector can be written as :

k $= (\hat{\imath}, \hat{j}, \hat{k})$, where

$\hat{\imath} = cos(\psi)cos(\theta)$

$\hat{j} = 1sin(\theta)$ *1 is assumed as the length of the k vector

$\hat{k} = sin(\psi)cos(\theta)$

To obtain the **up** vector, from now called v, and the side vector (s) (see figure 4.10) operations are shown next (3D Application):

```
[...]
toRad=2*np.pi/360
toDeg=1/toRad

arduino = serial.Serial('com13', 115200)
LineArdu = arduino.readline()
LineArdu = LineArdu.decode('utf-8')
time.sleep(2)
datos = LineArdu.split(',')

mano1 = box (pos = vector(0,0,0),
length=4,
height=0.6,
width=4,
color = color.orange
, opacity = 1)

sensor =  box (pos = vector(0,.1,0),
length=1,
height=.6,
width=1,
color = color.red, opacity = .5)

d1 = box (pos = vector(3,0,-1.5),
length=3.5,
height=0.5,
width=.9,
color = color.orange, opacity = 1)
[...]
k1 = np.cos(yaw)*np.cos(pitch)
k2 = np.sin(pitch)
k3 = np.sin(yaw)*np.cos(pitch)
k = vector(k1,k2,k3) #Vector that points towards
the front of the
figure

y = vector(0,1,0) #Reference vector used to obtain
```

```
side and up vectors.
s = cross(k,y) #Cross product of vector k and
a reference vector y

v = cross(s,k) #Cross vector of the side vector
points towards positive"y" and
it is perpendicular to "k" vector

vrot = v*np.cos(roll) + cross(k,v)*np.sin(roll)
hand.up = vrot
hand.axis = k
[...]
```

As mentioned in section 1.8, serious games should follow some recommendations to improve patient engagement. This system gives continuous data and no calibration is required, also it is easy to handle. Hence, is applicable to use with this software focusing on rehabilitation. Further work with patients is required to personalize the animation and visualizations.

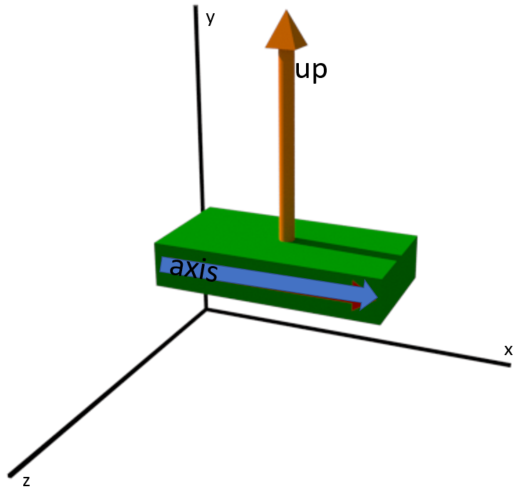


Figure 4.11: "Axis" and "Up" vectors used as reference

SQlite3

To manage the patients and the input of data databases (DB) are presented as tools to storage the information. DB are built with Python with SQLite3 library which is a server-less database, that is to say, there is not need of installing any server to work In the information below, it is written in a general way how the main commands of this library were used in this project work.

DB connection

sqlite3.connect("NAME") as the name suggests, stablish the connection with the database:

```
con = sqlite3.connect("databases/patients.db")
```

Building the DB

variable.cursor() makes an object to interact with the database:

```
conexion = con.cursor()
```

cursor.execute([...]) this command is used to interact with the database, here is shown how to create one:

```
conexion.execute("""create table patients(
                                        ID integer,
                                        name text,
                                        age integer,
                                        sex text

                                    )""")
con.commit() #Saves the data
```

Accessing the DB

First, it is shown how to access an item from the database using ID value as reference, as required in the **Consult** window (see figure 4.12, a))

```
sql="select ID, name,age,sex
           from patients where ID=?" #ID vale is gotten from
                                      #the tkinter entry box
           cursor.execute(sql, datos)
           cursor.fetchall()
```

Second, it is shown how to see all items in the database, as required in the **List all** window (see figure 4.12, b))

```
sql="select ID, name,age,sex from patients"
           cursor.execute(sql)
           return cursor.fetchall()
```

Thirth, it is shown how to insert an item into the database, used in the **Add Patient** Window:

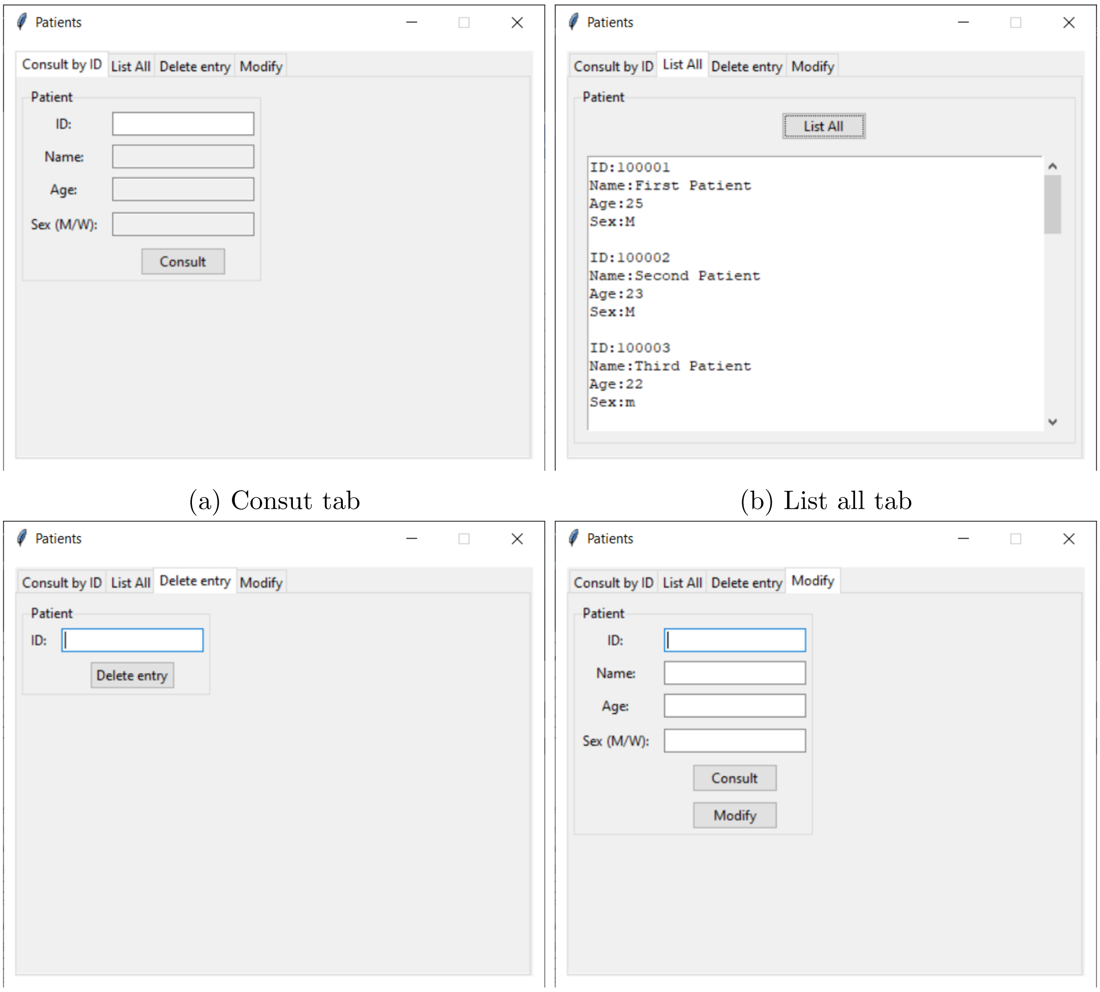
```
sql="insert into patients(name,ID,age,sex)
        values (?,?,?,?)"
        self.creartablapaciente(datos[1])
        cursor.execute(sql, datos)
        cursor.fetchall()
```

Fourth, it is shown how to delete any item from the database using its ID as reference, used in the **Delete** tab (see figure 4.12, c)):

```
sql="delete from patients where ID=?"
            id=(datos[0])
            remove('databases/'+id+'.db')
            cursor.execute(sql, datos)
            cone.commit()
```

Finally, the last option mentioned here allows to update the information from the database using the ID as reference (see figure 4.12, d)):

```
sql="update patients set ID=? , name=? ,
            age=? where ID=?"
            cursor.execute(sql, datos)
            cone.commit()
```



(a) Consut tab (b) List all tab

(c) Delete tab (d) Modify tab

Figure 4.12: Patients Window

As shown in figure 4.12, Tkinter also gives the option to add different tabs within a window, as schematically shown next:

```
self.NOTEBOOKVARIABLENAME = ttk.Notebook(self.MAINWINDOW)
#written in
#__init__ function

#Each tab was declared in a different function (def tab(self))
self.TABVARIABLENAME = ttk.Frame(self.NOTEBOOKVARIABLENAME)
self.cuaderno1.add(self.TABVARIABLENAME, text="TABNAME")
```

4.2.3 Matplotlib, Pandas, and Sklearn

Matplotlib library was used to plot the data for analysis (figs. 5.1,5.2,5.3, and 5.4.). Pandas was used to import the file with the information of the movement and create a a dataframe with it. Finally, Sklearn was used to implement PCA in the data measured (fig. ??). Inforsn obtained with the device includes the change in angles for each axis x, y, z.

This first portion of code is used to load the dataset from a *comma separated values (.csv)* file previously loaded from the information of the sensors

```
#The structure of the data is written as follows:
#A, 0.4648063182830810 5, 18.36 , 2.81 , −0.03 , 0.41 , 0.80 , 0.05
#Then, each column is named:
name_cols = ['name','time','x1','y1','z1','x2','y2','z2']
#But for analysis, only those columns with numbers are used:
cols = ['time','x1','y1','z1','x2','y2','z2']
# The word "MOTION" is replaced by the correspondant name for
# later analysis
MOTION = pd.read_csv('MOTION.csv', header = None, skiprows=1,
names=name_cols)
```

Next is shown the code to plot the angle for each axis,x, y, z, vs. time for analysis and interpreation.

Figures 5.1, 5.2, 5.3, 5.4, are obtained from similar code as follows. All the repetitions are plotted in the same graph showing trending in data obtaining for each motion.

```
MOTION.plot(kind = 'scatter',
 x= 'time',
 y = 'x1',
 c = 'b',
 title = "MOTION X")
MOTION.plot(kind = 'scatter',
 x= 'time',
 y = 'y1',
 c = 'b',
```

```
 title = "MOTION Y")
MOTION.plot(kind = 'scatter',
 x= 'time',
 y = 'z1',
 c = 'b',
 title = "MOTION Z")
plt.show()
```

Next step obtains the data from the Principal component analysis, where *StandardScaler()* is used to stantardize the data. Standardize features by removing the mean and scaling to unit variance. The standard score of a sample x is calculated as:

z = (x - u) / s

where *u* is the mean of the training samples, and *s* is the standard deviation of the training samples.

```
ss = StandardScaler()
MOTION [cols] = ss.fit_transform(MOTION[cols])
pca2 = PCA(n_components = 2,
random_state = 42)
pca2 = pca2.fit_transform(flexion[cols])

PCA_MOTION = pd.DataFrame({'PCA1' : pca2[:,0],
'PCA2' : pca2[:,1],
'Name' : MOTION['name']})
plt.show()
```

The above code is used to reduce dimensionality of the data from 7 variables *['time','x1','y1','z1','x2','y2','z2']* to 2 principal components.

Chapter 5

Results, interpretation and discussion

5.1 Data Analysis

To evaluate if the motion recorded is consistent and useful to differentiate motions of the wrist, several samples of the movements were taken.Twenty repetitions of each movement, flexion, extension, adduction, and abduction were graphed and are shown next. The repetitions are superimposed and serve to check how the data is similar for the same motion for each repetition, with small changes observed.

For flexion motion, the results of the data collection are shown in figure 5.1. In the **X** axis is possible to see how the angles decreases for one of each of the repetitions. **a)** shows how the angle decreases similarly for all the motions recorded, **b)** does not show meaningful changes with a range of angles which values are mainly between -2° to 7°, **c)** shows a trending of increase and decrease of data.

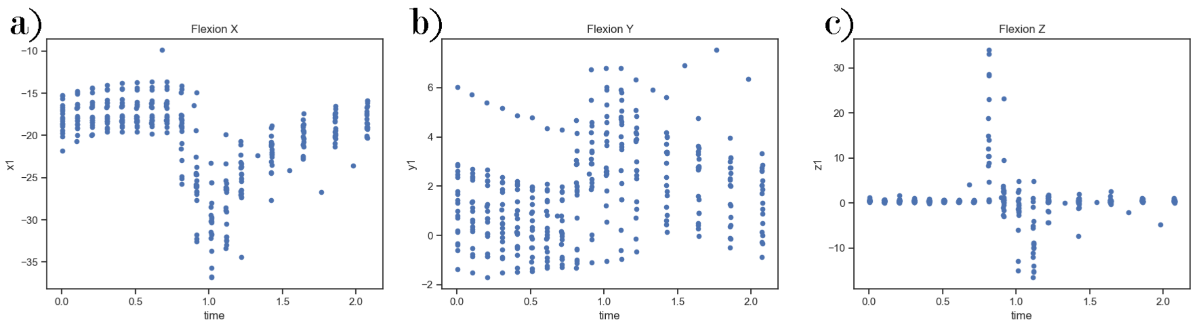


Figure 5.1: Plot in X, Y , and Z axis for 20 repetitions of flexion motion.

Figure 5.2 shows the values recorded for extension motion. **a)** shows a clear increase in the values for the angles. **b)**, similar to flexion motion (fig. 5.1), although slightly broader, motion is in a range of (-5,10)°. **c)** shows trending in motion for axis z, where values are similar to those found in **c)** in the Flexion plot.

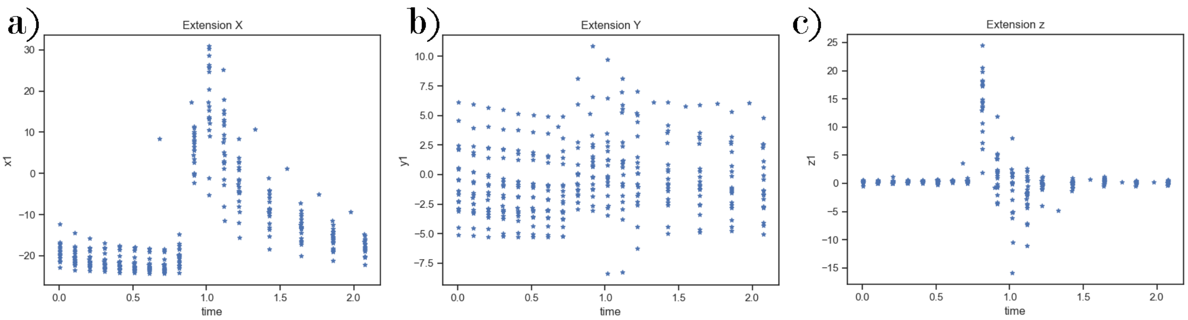


Figure 5.2: Extension Motion, a) angles in "X" axis, b) angles in "Y" axis, and c) angles in "Z" axis.

Figure 5.3 contains plots for adduction motion. **a)** shows a small change as an increase in the "X" axis for every repetition, this change is about 10°. **b)** shows no meaningful changes, as the data remains similar for each repetition. **c)** shows two peaks for the "Z" axis within this motion, first the values diminish, then increase to a positive vale for value of approximately 40° for each peak.

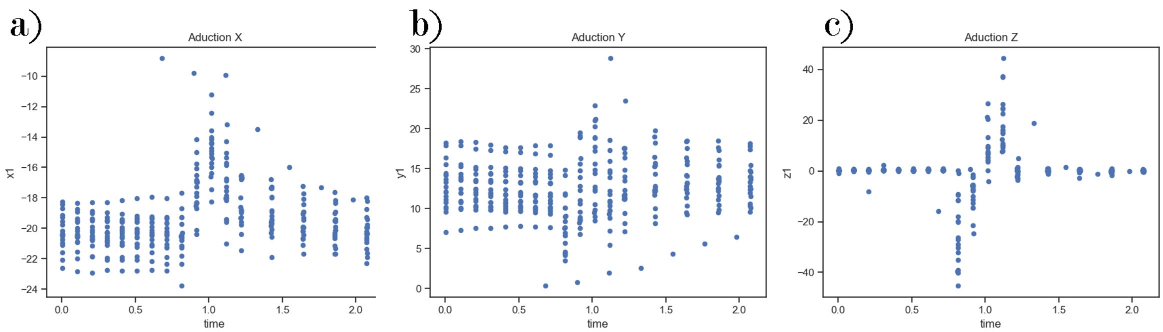


Figure 5.3: Adduction Motion, a) angles in "X" axis, b) angles in "Y" axis, and c) angles in "Z" axis.

Figure 5.4 shows the values recorded for abduction motion. **a)** and **b)** show small but meaningless changes. However, for **c)**, there are two peaks (similar to adduction motion) where first the values increase (almost until 60°), to reduce later (above -40°).

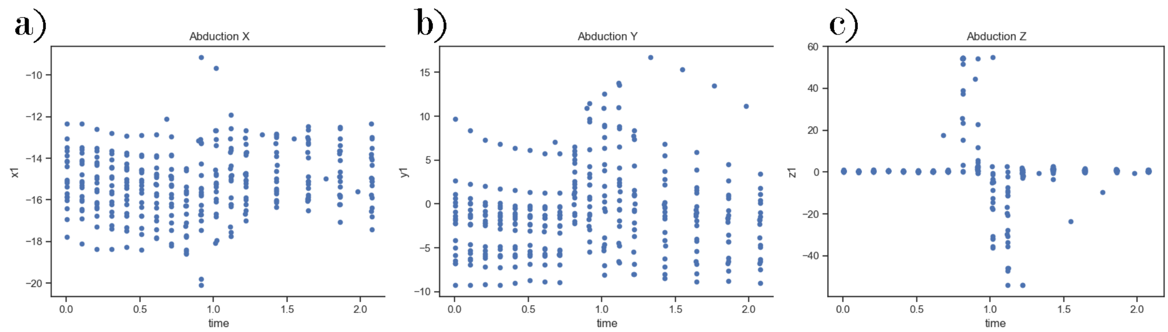


Figure 5.4: Abduction, deviation a) angles in "X" axis, b) angles in "Y" axis, and c) angles in "Z" axis. .

As seen in figures 5.1, 5.2, 5.3, 5.4, data from the sensors gives information that can be used to classify those motions, because, although MPU6050 does not give accurate data for "z" axis motion, it is possible to differentiate adduction and abduction checking if the positive or negative peak come first. For flexion, and extension motions, there is a clear difference, mainly visible in the "X" axis, that could help to easily identify which motion was made.
MPU6050 sensors can display accurately flexion, extension, pronation and supination. However, it shows some errors while displaying adduction and abduction, issue caused because of the lack of accelerometer data for the *"z"* axis or yaw, which is estimated from the other axis and only from the gyroscope, what makes imprecise the application of the complementary filter for this angle. Taking this plots, it is posible to observe that the device is precise with the measurements, and accurate in relationship with flexion and extension. Abduction and aduction are not accurate within this work because of the sensors and the problem mentioned with the *"z"* axis

To evaluate the use of machine learning with this sensors, Principal component analysis (PCA) were calculated to datasets corresponding to each movement.In order to generate a code that allows evaluating different movements, it was decided to use the PCA method. It was limited to two main components, as observed in figure 5.5. PCA plot shows that aduction is clearly differentiated in comparison with the other motions. Flexion and extension are slightly differentiated. However, abduction is harder to differentiate because, as seen in the plot, it is superimposed by extension and flexion partially. This noise can be explained by the quality of the data obtained from the sensors.

Finally, a system connected to local databases to store the information from the patients was developped. Also a 3D environment where the motion of the hand is replicated and the angles shown in the screen can be used as digital goniometers to estimate the evolution of the patient, however it requires more accurate sensors to display correctly the motion in every axis.

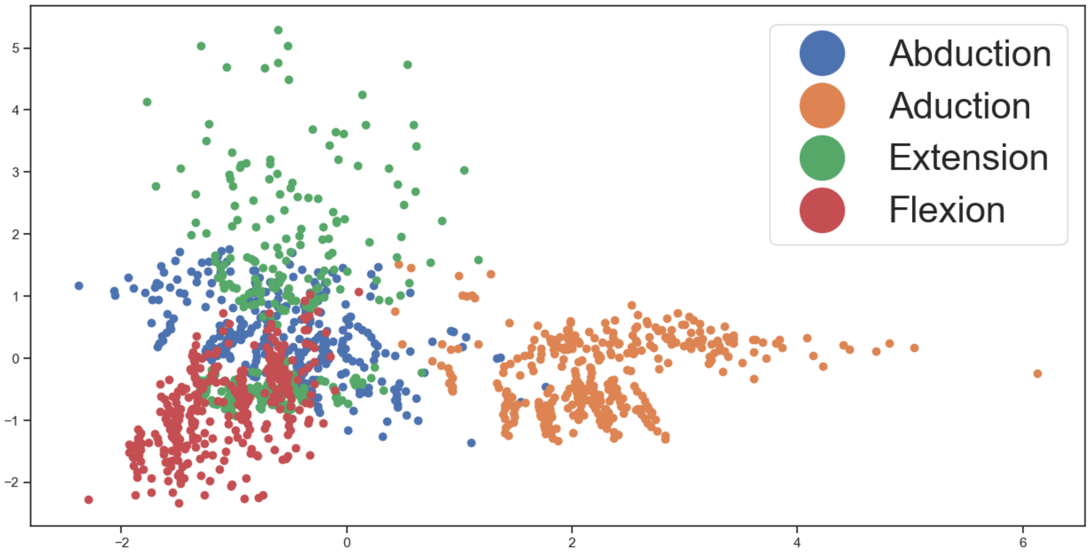


Figure 5.5: PCA data for basic wrist motion

Chapter 6

Conclusions and recommendations

6.1 Summary

It is possible to develop a low cost device (hardware and software) which function is to aid in the rehabilitation of the wrist, using open source platforms. In this case, type Arduino Nano microcontroller was used with two inertial sensors MPU6050. It shows promising results for discrimination of the basic motion of the wrist as well as a good system to store the data from the patients even if the measurement for the "Z" was a little confusing because of the lack of information from the accelerometer for this axis. A serious game was developed in order to visualize the movements of the hand during rehabilitation, and also the system allows us to count with the physical information about the progress of the patient. In conclusion, it can be stated that it is possible to develop a low-cost system aimed at improving the quality of physical rehabilitation from the use of open sources, both hardware and software. The hardware composed of an Arduino microcontroller and two MPU6050 inertial sensors had a cost of less than $20, however, measurements can be improved using more accurate sensors, such as the BNO0055 sensors whose price mounted on a board costs about $40, and which off plate they cost about $10 each. This low cost is implemented with the possibility of adding "n" sensors to the system using different connection methods or other types of microcontrollers. Even if the device could not be implemented because of pandemics caused by COVID19 virus, it shows promising features in relationship with its use because of its low cost in production, ease of maintenance and user friendly programming. Regarding the use of software, the use of Python allows access to the community and to all free content developed. As can be validated in this project, Python provides the tools to make the connection to the microcontroller with PySerial, it also gives access to create and modify databases with SQlite3, as well as different tools oriented to mathematical calculation and data graphing (pandas, sklearn, matplotlib). Finally, it also gives the option for creating 3D animations with which you can interact and perform simulations through the VPython library. Only some of the libraries used in this project were mentioned, however, the Python community is constantly updated and in addition to using libraries and projects already created, you can contribute with projects like this to strengthen this community.

6.2 Future work

For future work, the system will be implemented using BNO055 sensors and the exercises available will be also increased as well as the 3D environment, because BNO055 gives more accurate data and also includes magnetometer and gives quaternions for further operations. As well, the system will be implemented in a rehabilitation center to personalize it an adapt it for further use and telerehabilitation taking advantage of the advaces in artificial intelligence. Future implementation should be carried in physical rehabilitation centers with the support of therapists, patients and other students to improve and personalize the system.

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