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MASTER'S THESIS IN INDUSTRIAL AUTOMATION ENGINEERING - ROBOTICS
AND MECHATRONICS

**Development and assessment of a
robotic upper limb rehabilitation
system for multiplanar reaching
exercises and IMU-based joint
activation analysis**

Candidate:
Samuele Masciadri
Mat. n. 562315

Supervisor:
Prof. Antonella Ferrara

Co-Supervisor:
PhD. Chiara Alessi

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Abstract

Upper-limb robotics rehabilitation is increasingly moving towards end-effector collaborative robots used in industrial environment, which still allow for repeatable exercises and data acquisition on subject movements without using more expensive dedicated solutions.

Among the exercises available on these systems there is the Center-Out Point-To-Point (CO-PTP), in which the subject holds the robot's end-effector and then moves it from a central point to one of eight targets arranged on a circumference, before returning to the center. The exercise is effective because it combines repetitive, task-oriented reaching movements in multiple directions with real-time visual feedback of the trajectory. It also allows for the evaluation of movement quality metrics correlated with clinical scales for each direction.

AS-ULDAR, an upper limb rehabilitation platform equipped with a graphical interface (GUI) and developed by the Intelligent Robotics Lab of the University of Pavia, allows CO-PTP to be performed with a Franka Emika Panda robot, in its original form only in a single plane, the horizontal one.

Studies in the literature [23] suggest that it is more advantageous to stimulate the subject towards movements that require greater joint engagement, rather than the more comfortable ones; to apply this principle it is therefore necessary to understand, for each joint, which directions of movement require greater excursion. Suppose that, during a rehabilitation session, the robot must pass an object to a subject who is having difficulty in adducting/abducting the shoulder; to further stimulate this movement, it will be necessary to know which reaching movement most activates this joint.

To answer this question, the platform has been updated to allow CO-PTP on three working plane: horizontal, sagittal, and frontal. The robot's motion was constrained to the selected plane via a paired control law with a virtual elastic constraint along the axis normal to the plane.

Once extended, the platform was used to collect data on 12 healthy subjects and perform an exploratory statistical analysis. Specifically, the data were collected using Xsens inertial sensors. Subsequently, the ranges of variation of each arm joint (ROM) were calculated, for each direction of movement and for each plane. The joints analyzed were: SFE, SAA, SIER and EFE, which represent the shoulder flexion-extension, shoulder adduction/abduction, shoulder

internal-external rotation and elbow flexion-extension movements respectively.

For each plane, a statistical analysis was then performed to determine which reaching movements allowed by the CO-PTP result in a greater variation in the angle extension of each joint. ROMs were compared between directions using repeated measures ANOVA, or using Friedman tests when the assumption of normality was not verified (Shapiro-Wilk test), followed by pairwise post-hoc comparisons (t-test or Wilcoxon test for paired data) with a significance level of 0.05.

The results show that the direction dependence of the ROM increases as the vertical component of the plane increases. In the horizontal plane, no joint shows significant differences between directions which pass post-hoc comparisons, although elbow flexion-extension is the dominant joint; in the sagittal plane, the effect is significant for elbow flexion-extension, which is more stressed in directions that tend forward and upward relative to the subject; in the frontal plane, the effect is significant for all four joints, particularly for shoulder adduction/abduction, consistent with the raising and lowering movement of the arm. Even where the results are not statistically significant, they are consistent with a reasonable pattern consistent with the anatomy of movement; however, this pattern will need to be investigated in a larger sample of subjects.

In conclusion, the analyses conducted allow us to observe reasonable patterns, but they play an exploratory role. Since the results are positive, we might consider performing the same data analysis on a larger sample of subjects to exploit the results in the future in rehabilitation systems that encourage movement in certain directions, such as through handover or reaching exercises.

Sommario

La riabilitazione robotica dell'arto superiore si sta orientando sempre più verso i robot collaborativi a end-effector utilizzati in ambito industriale, i quali consentono comunque di eseguire esercizi ripetibili e di acquisire dati sui movimenti del paziente senza ricorrere a soluzioni dedicate più costose.

Tra gli esercizi disponibili su questi sistemi vi è il Center-Out Point-To-Point (CO-PTP), in cui il paziente impugna l'end-effector del robot per poi spostarlo da un punto centrale verso uno degli otto target disposti su una circonferenza, per poi tornare al centro. L'esercizio è efficace perché combina movimenti di reaching ripetitivi e orientati al compito in più direzioni con un feedback visivo della traiettoria eseguita in tempo reale, inoltre permette di valutare, per ciascuna direzione, metriche di qualità del movimento correlate con scale cliniche.

AS-ULDAR, una piattaforma per la riabilitazione dell'arto superiore dotata di interfaccia grafica (GUI) e sviluppata dall'Intelligent Robotics Lab dell'Università di Pavia, permette di svolgere il CO-PTP con un robot Franka Emika Panda, nella sua forma originale solo in un unico piano, quello orizzontale.

Studi in letteratura [23] suggeriscono che è più vantaggioso stimolare il paziente verso movimenti che richiedono un maggiore impegno articolare, piuttosto che verso quelli più comodi; per applicare questo principio è quindi necessario capire, per ciascun giunto, quali direzioni di movimento richiedono un'escursione maggiore. Supponiamo che, durante una seduta riabilitativa, il robot debba passare un oggetto ad un paziente che ha difficoltà nel movimento di adduzione/abduzione della spalla; per stimolare maggiormente tale movimento sarà necessario conoscere quale movimento di reaching attiva di più tale articolazione.

Per rispondere a questa domanda, la piattaforma è stata aggiornata in modo da consentire il CO-PTP su tre piani di lavoro: orizzontale, sagittale e frontale. Il moto del robot è stato vincolato al piano selezionato tramite una legge di controllo in coppia con un vincolo elastico virtuale lungo l'asse normale al piano.

Una volta estesa, la piattaforma è stata utilizzata per raccogliere i dati su 12 soggetti sani e svolgere un'analisi statistica esplorativa. Nello specifico i dati sono stati raccolti tramite sensori inerziali Xsens. Successivamente sono stati calcolati i range di variazione di ogni giunto del braccio (ROM), per ogni direzione di movimento e per ogni piano. I giunti analizzati sono stati: SFE, SAA, SIER ed

EFE, che rappresentano rispettivamente i movimenti di flesso-estensione della spalla, adduzione/abduzione della spalla, rotazione interna-esterna della spalla e flesso-estensione del gomito.

Per ogni piano è stata poi svolta un'analisi statistica per determinare quali movimenti di reaching permessi dal CO-PTP comportano una maggiore variazione dell'estensione dell'angolo di ciascun giunto. I ROM sono stati confrontati tra le direzioni tramite ANOVA a misure ripetute, oppure tramite test di Friedman quando l'ipotesi di normalità non era verificata (test di Shapiro-Wilk), seguiti da confronti post-hoc a coppie (t-test o test di Wilcoxon per dati appaiati) con un livello di significatività pari a 0,05.

I risultati mostrano che la dipendenza del ROM dalla direzione cresce all'aumentare della componente verticale del piano. Sul piano orizzontale nessun giunto presenta differenze significative tra le direzioni che superino i confronti post-hoc, sebbene la flesso-estensione del gomito risulti il giunto dominante; sul piano sagittale l'effetto è significativo per la flesso-estensione del gomito, maggiormente sollecitata nelle direzioni che tendono in avanti e verso l'alto rispetto al paziente; sul piano frontale l'effetto è significativo per tutti e quattro i giunti, in particolare per l'adduzione/abduzione della spalla, coerentemente con il movimento di sollevamento e abbassamento del braccio. Anche dove i risultati non sono statisticamente significativi, sono riconducibili ad un pattern ragionevole e coerente con l'anatomia del movimento; nonostante ciò, questo pattern dovrà essere indagato su un campione di soggetti più ampio.

In conclusione, le analisi svolte permettono di osservare pattern ragionevoli, tuttavia hanno un ruolo esplorativo; siccome il riscontro è positivo si potrebbe pensare di svolgere la stessa analisi dei dati su un campione di pazienti più ampio per poterne sfruttare i risultati in futuro in sistemi riabilitativi che incentivino il movimento in determinate direzioni, ad esempio tramite esercizi di hand-over o di reaching.

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List of Acronyms

ANOVA	Analysis of Variance
AS- ULDAR	Auto-calibrating System for Upper-Limb Disability Assessment, Neurological and Occupational Rehabilitation
CO-PTP	Center-Out Point-To-Point
DH	Denavit–Hartenberg
EFE	Elbow Flexion/Extension
FCI	Franka Control Interface
GUI	Graphical User Interface
IMU	Inertial Measurement Unit
IP	Internet Protocol
ROM	Range of Motion
ROS	Robot Operating System
SAA	Shoulder Adduction/Abduction
SCARA	Selective Compliance Assembly Robot Arm
SFE	Shoulder Flexion/Extension
SIER	Shoulder Internal/External Rotation
TCP	Transmission Control Protocol
UDP	User Datagram Protocol

Chapter 1

Introduction to Robotics and Robotic Rehabilitation

1.1 Introduction

This chapter has the aim to introduce the context of robotic rehabilitation, describing the main families of rehabilitation devices, the most common control strategies, and the motivation for adopting a cobot-based end-effector approach.

1.2 Introduction to Robotic Rehabilitation

Robotic rehabilitation is a field of biomedical engineering that uses robotic devices to support the motor recovery of subjects with neurological impairments. The increasing interest in these technologies is guided by the growing demand for rehabilitation services in contrast to the shortage of therapists, and the need to provide intensive, repetitive, and task-oriented training, which is recognised as essential for motor recovery [1].

Robotic systems can support rehabilitation by delivering highly repeatable training sessions while reducing therapist workload and providing objective quantitative measurements of subject performance. Compared with conventional therapy, they can maintain a prescribed training intensity over long periods and continuously collect sensor data that can be used both to adapt assistance in real time and to monitor subject progress throughout the rehabilitation process [2].

Clinical evidence supporting robot-assisted rehabilitation has progressively strengthened over the last two decades. Early reviews reported significant improvements in motor function and muscle strength, although the effects on daily life activities were less consistent [3]. More recent reviews and meta-analyses have generally confirmed the beneficial effects of robot-assisted therapy on upper-limb motor recovery compared with conventional rehabilitation; however, results may depend on subject characteristics and on the stage of recovery [3, 4].

According to their mechanical structure and physical interaction with the user, rehabilitation robots are commonly classified into two main categories: exoskeletons and end-effector systems [5]. Exoskeletons are wearable devices whose joints are aligned with the anatomical joints of the subject, enabling independent control of multiple limb segments. This capability is achieved at the expense of greater mechanical complexity and the need for accurate anatomical alignment, resulting in longer setup times and reduced adaptability across subjects [1, 5]. The end-effector family, used in this work, is introduced in the following section.

1.3 End-Effector Systems

End-effector systems interact with the subject through a single contact point, typically a handle, to which the limb is attached, while the resulting movement of the arm is generated through the natural kinematic coupling of the limb segments [2, 5]. Since forces are applied and measurements are acquired at a single contact point, these devices can be easily adapted to subjects with different anthropometric characteristics without substantial mechanical adjustments [2].

This simplified architecture offers some practical advantages, including lower mechanical complexity, reduced setup time, simpler control algorithms and greater tolerance to anatomical variability among subjects [1]. On the other hand, acting through a single interface limits the possibility of independently controlling or measuring individual joint motions, and redundancy in the subject's arm configuration may lead to non-physiological postures when the anatomical degrees of freedom exceed those controlled by the device [1, 2].

Despite these limitations, end-effector systems have demonstrated considerable effectiveness in upper-limb rehabilitation thanks to their simplicity and ease of clinical use. A representative systems is the MIT-Manus [8].

Many existing rehabilitation devices rely on dedicated mechanical architectures and custom-designed hardware, making them expensive and limiting their diffusion outside specialized rehabilitation centers [25]. These limitations have stimulated growing interest in the use of industrial collaborative robots (cobots), such as MIME [9], whose large-scale production, integrated safety functions, and modular hardware architecture make them attractive alternatives to custom rehabilitation platforms. Furthermore, recent studies have demonstrated the feasibility of clinician-oriented rehabilitation interfaces based on industrial robots, specifically by using the ROS 2 framework [6], and can potentially be used with any industrial robot.

The diffused availability, reliability, and flexibility of cobots enable the implementation of rehabilitation strategies without requiring dedicated robotic hardware, facilitating both research and potential clinical translation. For these reasons, and because of the mechanical simplicity and versatility of end-effector architectures, the rehabilitation system which is the object of this thesis is based

on an end-effector configuration based on an industrial collaborative robot.

1.4 Control Strategies

The clinical effectiveness of a rehabilitation robot is determined not only by its mechanical structure but also by the adopted control approach and by how the device interacts with the subject. A recurring conclusion in the literature is that recovery is favored not only by maximizing the number of repetitions, but by maintaining the subject's attention and effort during training, and that assistance adjusted to the subject's current ability tends to produce better results than a fixed, predetermined pattern [1].

Devices for upper-limb rehabilitation can be grouped according to the kind of motion assistance they provide and are divided in active, passive, haptic, and coaching. An active device incorporates at least one actuator and is therefore able to move the limb, which is necessary when the subject is too weak to perform the exercise unaided. A passive device, by contrast, cannot produce motion and is fitted only with resistive elements such as brakes; consequently, it suits subjects who already have some voluntary movement, and it tends to be lighter and cheaper than its active counterpart. Haptic refers to use a physical sensations to provide feedback during an interaction or simulation environment. Coaching refers to the robot's role in guiding the rehabilitation exercises. [10].

It is worth distinguishing the device from the exercise it delivers. In fact, an actuated device can be used for a passive exercise, in which the subject stays inactive while the machine guides the limb through a controlled range of motion; continuous passive motion training is the typical example. In an active exercise, instead, the subject contributes to the movement, possibly with some help from the device [1].

Among the high-level control approaches designed to promote motor plasticity, assistive strategies help the subject in completing an intended movement, making the task easier and allowing a greater number of repetitions. Several variants exist, including approaches that act only when the limb varies from a reference trajectory, approaches that counterbalance the weight of the limb to reduce the force needed against gravity, and approaches that adjust parameters such as force or path according to the subject's measured performance [10]. Those approaches belong to the Assist-as-needed category [26].

A second family of high-level approaches sets the subject a challenge rather than offering help. Resistive strategies oppose the intended motion to increase the subject's effort and engagement; other variants deliberately amplify movement error, on the premise that learning is error-driven, or constrain the unaffected limb to encourage use of the impaired one [11]. A drawback of strategies that adapt their support to the subject is so-called slacking: when assistance is excessive, the subject may reduce effort and attention, which can reduce the benefit of the training. This effect is more pronounced with approaches mainly

triggered by the subject, since the person may learn to supply only the minimal activation needed to set the assistance in motion [10].

Chapter 2

Related Works and Rationale of the thesis

2.1 Introduction

The contribution of this thesis stands at the intersection of three lines of research. The first is the idea, developed in the context of human–robot interaction, that a machine can be more beneficial to a person when it deliberately stimulates movement rather than when it minimizes effort. The second is the biomechanical observation that the recruitment of the upper-limb joints depends on the direction of the movement, an observation that can be quantified and tested with the statistical methods introduced in the previous chapter. The third is the recent effort to bring rehabilitation onto general-purpose collaborative robots by means of clinician-friendly software, which gives the platform on which this work is built.

This chapter reviews the works from which the present system built its main ideas and clarifies how the thesis positions itself with respect to them. The purpose is to give an overview of the three specific studies that shaped the design of the assessment framework.

2.2 Stimulating Movement Variability: Productive Inconvenience

A first source of inspiration comes, somewhat surprisingly, from industrial human–robot collaboration. Zolotas et al. [23] study robot-to-human handovers, the common task in which a robot passes an object to a person, and they question assumption that the robot should always make the exchange as convenient as possible for the receiver. Most previous approaches compute the exchange location to keep the person in a stable, comfortable posture, typically by keeping the projection of their center of mass well within their base of support. The

authors instead compare this conventional “assistive” behavior with a “stimulating” one that deliberately push the receiver towards more varied postures, temporarily displacing their center of mass rather than stabilizing it.

The authors summarize this finding with the notion of productive inconvenience: a machine that is slightly less convenient can keep the human more attentive and engaged, and this engagement can be beneficial in the long run.

An exercise that keeps challenging the subject, and that moves the effort towards the movements the subject performs least well, is exactly the kind of productively inconvenient interaction that motor recovery is known to reward.

This principle explains, in the AS-ULDAR system, why to influence the exercise towards the movement directions that require a determinate joint angle more, and it motivates the need to identify those directions.

An idea can be to identify the directions in which a subject predominantly uses certain joints and then adapt the exercise to emphasize movement in those directions, with the aim of increasing the load on the targeted joints.

2.3 Movement Direction and Joint Demand

If the exercise has to be directed towards different directions, one must first establish that the demand on the upper-limb joints really does depend on the direction of the movement. This is precisely the question investigated by Kikuchi et al. [20] in a kinematic study of multi-directional reaching. The authors asked a group of healthy adults to perform reaching movements from a central starting point towards targets arranged on a circle around it, sampling the direction at regular angular steps over along the circle, with each movement performed at a controlled pace and one direction tested at a time. Using a three-dimensional motion analyzer and a set of markers placed on anatomical landmarks, they reconstructed the motion of the shoulder girdle, the shoulder joint and the elbow during the task.

For each joint they computed the range of motion in every direction and then tested whether the direction of the movement had a significant effect on that range of motion. The analysis revealed a clear directional specificity: the joints are recruited in different ways depending on where the target lies, and the combined motion of the joints follows characteristic spatial patterns. On this basis the study classifies the directions into those in which the shoulder mainly moves, those in which the shoulder girdle and the elbow mainly move, and those in which all the joints contribute together, and it concludes that the difficulty of a reaching movement depends on its direction through the particular combination of joints it requires.

This work provides both conceptual justification and the methodological template for the analysis developed in this thesis. Conceptually, it establishes that “the most critical direction” for a subject is a well-defined notion, based on joint

kinematics rather than on the therapist’s impression. Methodologically, it shows that the appropriate way to test it is an analysis of variance on the range of motion across directions, complemented by post-hoc comparisons, exactly the pipeline that Chapter 8 adapts to the AS-ULDAR data, transposing it from the single horizontal reaching task of the original study to the several working planes and the four joints supported by the system.

2.4 Clinician-Friendly Interfaces on Industrial Robots

The final line of research concerns the platform on which the present system is built. Alessi et al. [6] propose a flexible, clinician-oriented software for upper-limb rehabilitation with industrial collaborative robots. Rather than relying on a dedicated rehabilitation machine, their framework run on ROS2 and can, in principle, be coupled with any torque-controlled collaborative robot compatible with ROS2; this can also be an approach that lowers cost and improves availability with respect to purpose-built devices. The software collects the kinematic and dynamic data produced during the exercises, computes from them a set of quality metrics that have been shown to correlate with established clinical scales and uses statistical tests to detect improvements or regressions across sessions.

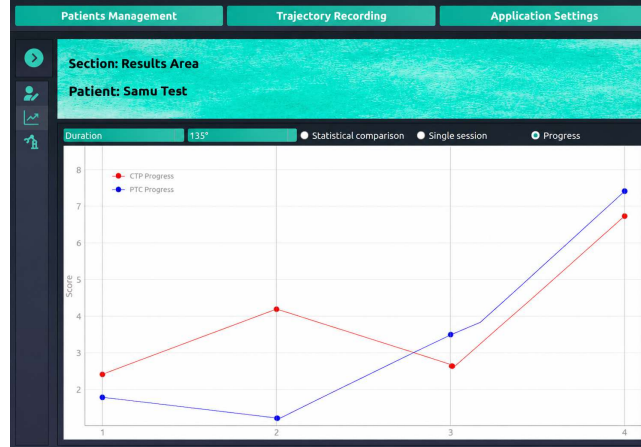


Figure 2.1: GUI progress page

A distinctive feature of their framework is that the central exercise, the CO-PTP (consisting in moving the arm by grasping the robot in different directions, better explained in 4.6.2), is not delivered with a fixed sequence of targets: the probability that a given target is proposed to the subject depends on the subject’s past performance, so that the directions in which the subject performs worst are prioritized.

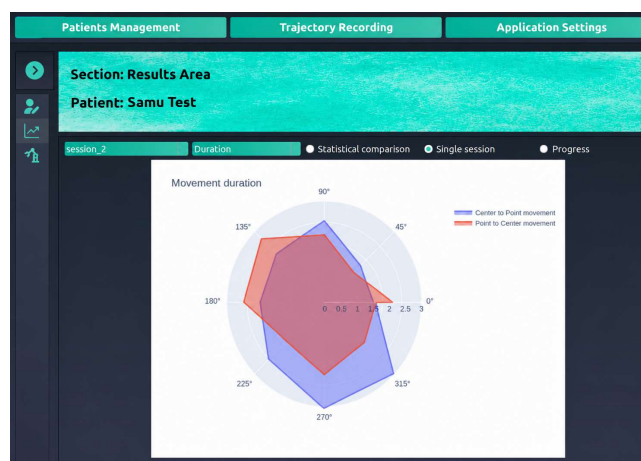


Figure 2.2: CO-PTP visual feedback

This is a concrete realization, inside a rehabilitation device, of the principle of stimulating the most demanding joints movements discussed above. The interface, described in detail in the next chapter, is the basis on which the work of this thesis is carried out.

2.5 Rational of the Thesis

This thesis combines an idea, a method and a platform. From the work on productive inconvenience, it takes the idea that a rehabilitation exercise should stimulate the subject towards the movements that cost the most usage of a joint and not the easier movement. From the study on multi-directional reaching, it takes the method for identifying those movements, namely an analysis of variance on the range of motion across directions. From the clinician-friendly interface it takes the platform on which the CO-PTP with visual feedback is implemented, together with its adaptive exercise. The specific contribution of the thesis is to modify the GUI to make the CO-PTP usable on several working planes and to exploit the new asset of the system to implement a statistical assessment of the directional distribution of joint ROM. The remaining chapters describe the interface as it was found, the communication and multi-plane extensions that were required, the statistical assessment that was added, the experimental setup and laboratory proves.



Figure 2.3: Graphical abstract

2.6 Thesis Structure

This thesis from this chapter onward is structured as follows:

- **Chapter 2** reviews the related work that shaped the design of the system: the idea of stimulating movement variability, the dependence of joint demand on the movement direction, and the clinician-friendly interface based on industrial robots.
- **Chapter 3** presents the preliminary concepts in order to understand the work: the fundamental of robotics, the kinematic and dynamic model of manipulators, the kinematic model of human arm.
- **Chapter 4** describes the hardware and software tools used in this project: the ROS 2 middleware, the UDP protocol, the Franka Emika Panda collaborative robot, the Xsens MVN inertial sensors and the AS-ULDAR graphical user interface.
- **Chapter 5** recalls the statistical background on which the assessment relies: the logic of hypothesis testing, the range of motion as a kinematic descriptor, the analysis of variance with its assumptions and post-hoc comparisons.
- **Chapter 6** describes the concrete work carried out on the communication between the inertial sensors and the interface and the extension of the exercise to several working planes, together with its validation in simulation.
- **Chapter 7** explains how the experimental setup was disposed of and successively the sensor calibration and tests.
- **Chapter 8** introduces the main contribution of the thesis: a statistical assessment of the directional distribution of joint ROM, and integration into the interface.
- **Chapter 9** discusses the results of the collected data after the statistical evaluation.
- **Chapter 10** shows the final considerations of this work by enlightening the obtained results and the criticism and discussing future work that can be done.

Chapter 3

Preliminary Concepts

3.1 Introduction

The following chapter has the purpose to presents the preliminary concepts required to understand the work: the fundamentals of robotics, the kinematic and dynamic modelling of manipulators, and the kinematic model of human arm.

3.2 Fundamentals of Robotics

Robotics can be described as the discipline that studies how to establish an intelligent connection between perception and action. Under this view, a robot is not characterized by its outward appearance but by its ability to modify the environment in which it operates, carrying out actions that depend both on acquired information and on control decisions [27]. This functional definition is convenient for engineering purposes because it shifts attention away from anthropomorphic imagery and toward the subsystems that a robot must integrate to behave purposefully [7].

A robotic system is a complex assembly of cooperating subsystems [27]. The mechanical system provides the physical body and is generally equipped with a locomotion apparatus, a manipulation apparatus, or both [27, 28]. The ability to exert actions on the environment is supplied by an actuation system, which powers the mechanical components through actuators and related drive elements [7]. Perception is committed to a sensory system that collects information on the internal status of the structure and on the external status of the environment through proprioceptive and exteroceptive sensing [27]. Typical proprioceptive variables include joint position, velocity, and acceleration. Finally, a control system links perception to action, commanding task execution while respecting the robot's objectives and coordinating motion through sensor processing and actuator commands [27, 28].

Because these subsystems draw on mechanics, control theory, computer science, electronics, and mathematical modelling, robotics is intrinsically an interdisciplinary field [7, 27].

Among the activities required to make a robot operate autonomously, three are particularly relevant for this thesis: modelling, planning and control. Modelling is concerned with deriving the mathematical relationships that describe the motion of the structure and the forces that produce it; planning addresses the generation of suitable motions for the assigned task; control determines the actions that the actuators must produce so that the planned motion is executed.

The theoretical background presented in this chapter is based on the classical formulation found in [7]. Unless otherwise stated, definitions and notation follow this reference.

3.2.1 Mechanical Structure and Robot Manipulators

The defining feature of a robot is its mechanical structure, and a first useful classification distinguishes robots with a fixed base, the manipulators, from those with a mobile base. The work developed here is concerned exclusively with manipulators, which constitute the dominant class in industrial settings.

A manipulator can be schematized as a kinematic chain of rigid bodies, called **links**, connected by articulations, called **joints**. One end of the chain is fixed to a **base**, while the opposite end carries an **end-effector** that carries out the robot's intended task.

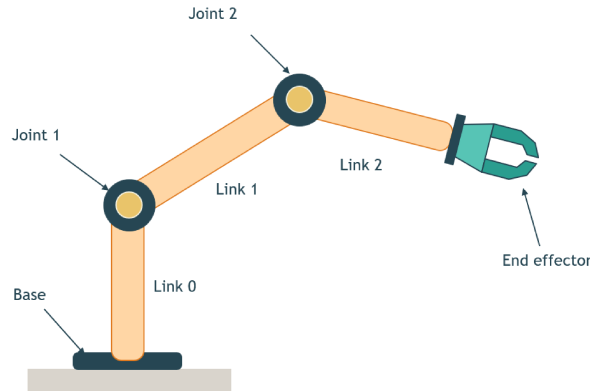


Figure 3.1: Schematic diagram of a robotic manipulator showing its links and joints.

Functionally, the structure is organized into an arm that provides mobility, a wrist that provides dexterity, and the end-effector itself. The fundamental structure is an open kinematic chain, in which a single sequence of links connects the two ends; when a sequence of links instead forms a loop, the manipulator contains a closed kinematic chain. In an open chain each joint contributes a single degree of freedom (DOF), so that the joint variable, a displacement or an

angle, fully describes the relative motion at that articulation. In a closed chain, the loop imposes constraints, and the number of degrees of freedom is therefore smaller than the number of joints.

Mobility is provided by the joints, which may be of two basic types:

- **Prismatic Joint:** A prismatic joint introduces a relative translation between the two links it connects
- **Revolute Joint:** Revolute joints introduce a relative rotation and are usually preferred for their compactness and reliability.

The way in which the degrees of freedom are distributed along the structure determines what tasks the manipulator can perform. Arbitrarily positioning and orienting a rigid body in three-dimensional space requires six degrees of freedom: three to place a point of the body and three to fix its orientation with respect to a reference frame. When the structure offers more degrees of freedom than the task strictly requires, the manipulator is said to be kinematically redundant, a property that can be exploited to gain dexterity, avoid obstacles or circumvent joint limits.

Listed below is a series of concepts that will be used in the remainder of the thesis.

Workspace: The workspace is the portion of the environment that the end-effector can reach and depends on the geometry of the structure and on the mechanical limits of the joints; it is usual to distinguish the reachable workspace, accessible with at least one orientation, from the smaller dexterous workspace, accessible with every orientation.

Robot Manipulator Geometries: Robot Manipulator Geometries are classifications of robot manipulators based on the type and sequence of their joints, counted from the base. These configurations determine the characteristic geometry of the manipulator and its workspace. The arm is responsible for positioning the wrist, while the wrist then orients the end-effector.

Cartesian Manipulator: A Cartesian arm uses three mutually orthogonal prismatic joints, so that each degree of freedom corresponds directly to a Cartesian coordinate; it offers high stiffness and constant positioning accuracy throughout a parallelepiped-shaped workspace, but limited dexterity. Replacing the first prismatic joint with a revolute one yields the cylindrical geometry, whose workspace is a portion of a hollow cylinder, while replacing a further prismatic joint with a revolute one produces the spherical geometry.

SCARA Manipulator: The SCARA geometry combines two revolute joints and one prismatic joint with parallel axes, providing high stiffness against vertical loads and compliance to horizontal loads, which makes it well suited to vertical assembly.

Anthropomorphic Manipulator: The anthropomorphic geometry uses three revolute joints, with the first axis orthogonal to the two parallel axes of the shoulder and elbow; by virtue of its similarity to the human arm, it is the most dexterous configuration and accounts for the largest share of installed industrial manipulators.

Orientation of the end-effector in space generally requires a wrist with at least three revolute degrees of freedom. The most favourable construction is the spherical wrist, in which the three revolute axes intersect at a single point. The key advantage of this arrangement is the decoupling of position and orientation: the arm is responsible for positioning the point of intersection, while the wrist determines orientation alone. This decoupling simplifies both the inverse kinematics and the analysis of singular configurations.

Industrial Robotics: Industrial robotics is the branch concerned with the design, control and application of robots in manufacturing, and it has by now reached the maturity of an established technology. Its characteristic trait is the operation within a structured environment whose geometric and physical characteristics are known in advance, so that only limited autonomy of the machine is required.

The first industrial manipulators emerged in the 1960s from the convergence of numerically controlled machine tools and teleoperators developed for handling radioactive material. Compared with these precursors, they introduced:

- versatility, through interchangeable end-effectors;
- adaptability to partly unknown situations, through sensing;
- positioning accuracy, through feedback control;
- repeatability, through programmability.

According to the Robot Institute of America, an industrial robot is “a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks” [7].

3.3 Kinematic Modelling

Kinematic analysis describes the motion of the structure with respect to a fixed reference frame, without considering the forces and moments that cause it. For a manipulator this means relating the joint positions to the position and orientation of the end-effector. Before this relationship can be written, it is necessary to recall how the pose of a rigid body is represented.

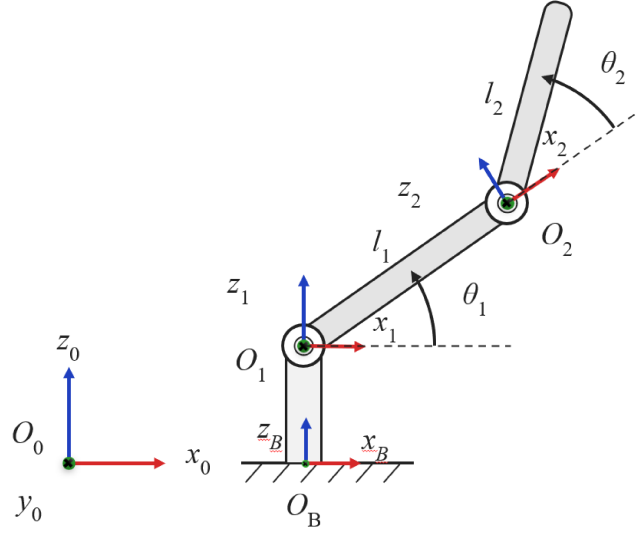


Figure 3.2: kinematic chain for showing reference frames

3.3.1 Pose Representation and Homogeneous Transformations

To describe the pose of a rigid body, a fixed reference frame is first defined. The position of the body is specified by the coordinates of a representative point with respect to this frame, while its orientation is specified by attaching a body frame to the rigid body and expressing the unit vectors of the body-frame axes with respect to the reference frame.

Collecting these unit vectors as the columns of a matrix yields the rotation matrix R which belong to the $SO(3)$ set that is contained in $R^{3 \times 3}$. Because the columns are mutually orthogonal and of unit norm, the matrix is orthogonal:

$$R^T R = I_3 \quad (3.1)$$

and its inverse coincides with its transpose; for a right-handed frame its determinant equals one. A rotation matrix carries three equivalent meanings:

- it describes the mutual orientation of two frames;
- it transforms the coordinates of a point between two frames sharing the same origin;
- it acts as an operator that rotates a vector.

Successive rotations in the axes of the current frame are composed by post-multiplying the corresponding matrices, and because matrix products do not commute, the order of rotations matters.

A rotation matrix has nine entries constrained by six orthonormality conditions, so only three independent parameters are needed to describe orientation; minimal representations such as Euler angles exploit this fact. Describing the pose of a

body, however, requires position and orientation together, and it is convenient to combine them.

Consider a generic point P in space and two frames, a reference frame $O_0-x_0y_0z_0$ and a second frame $O_1-x_1y_1z_1$. Let p^0 and p^1 be the coordinates of P expressed in the two frames, let o_1^0 be the position of the origin of Frame 1 with respect to Frame 0, and let R_1^0 be the rotation matrix of Frame 1 with respect to Frame 0. Elementary geometry then gives the coordinate transformation of the point between the two frames as

$$p^0 = o_1^0 + R_1^0 p^1 \quad (3.2)$$

which represents the (translation + rotation) of a vector between two different frames.

The corresponding inverse transformation follows by premultiplying both sides by R_1^{0T} and using the orthogonality of the rotation matrix, giving:

$$p^1 = R_1^{0T} p^0 - R_1^{0T} o_1^0. \quad (3.3)$$

For a compact notation, we can introduce the *homogeneous representation* of the vector p :

$$\tilde{p} = \begin{bmatrix} p \\ 1 \end{bmatrix}. \quad (3.4)$$

With this representation the rotation and the translation collapse into a single matrix belonging to the SE(3) set contained in $R^{4 \times 4}$, and the coordinate transformation becomes the plain product $\tilde{p}^0 = A_1^0 \tilde{p}^1$, where:

$$A_1^0 = \begin{bmatrix} R_1^0 & o_1^0 \\ \mathbf{0}^T & 1 \end{bmatrix} \quad (3.5)$$

is the homogeneous transformation matrix. Its upper-left 3×3 block carries the orientation of Frame 1 relative to Frame 0, its fourth column carries the position of the origin of Frame 1, and its bottom row is the fixed quadruple $\begin{bmatrix} \mathbf{0}^T & 1 \end{bmatrix}$.

The decisive property of this representation is that successive coordinate transformations can be expressed as:

$$\tilde{p}^0 = A_1^0 A_2^1 \cdots A_n^{n-1} \tilde{p}^n, \quad (3.6)$$

in which each A_i^{i-1} relates Frame i to the preceding Frame $i - 1$.

3.3.2 Direct Kinematics and the Denavit–Hartenberg Convention

The direct kinematics problem consists in computing the pose of the end-effector as a function of the joint variables. For an open chain of $n + 1$ links connected by n joints, a frame is attached to each link, and the pose of the last frame

relative to the first is obtained as the ordered product of the homogeneous transformations between consecutive frames:

$$T_n^0(q) = A_1^0(q_1) A_2^1(q_2) \cdots A_n^{n-1}(q_n), \quad (3.7)$$

where each matrix $A_i^{i-1}(q_i)$ depends on a single joint variable, q is the vector that contains the joint variables and belongs to $\mathbb{R}^3$; T is the homogeneous transformation matrix and belong to $T_n^0 \in \mathbb{R}^n \rightarrow \mathbb{R}^{4 \times 4}$.

The direct kinematics function is therefore recursive, which is convenient both for computation and for analysis.

The result becomes fully systematic once the link frames are placed according to a shared rule. The **Denavit–Hartenberg convention** provides such a rule by fixing how the axes of frame i are chosen:

- the z_i axis is aligned with the axis of joint $i + 1$,
- the x_i axis is taken along the common normal between z_{i-1} and z_i ,
- the y_i axis completes a right-handed frame.

With the frames placed in this way, the relative pose of two consecutive links is described by four parameters:

- a_i : link length
- d_i : offset
- ϑ_i : joint angle
- α_i : twist angle

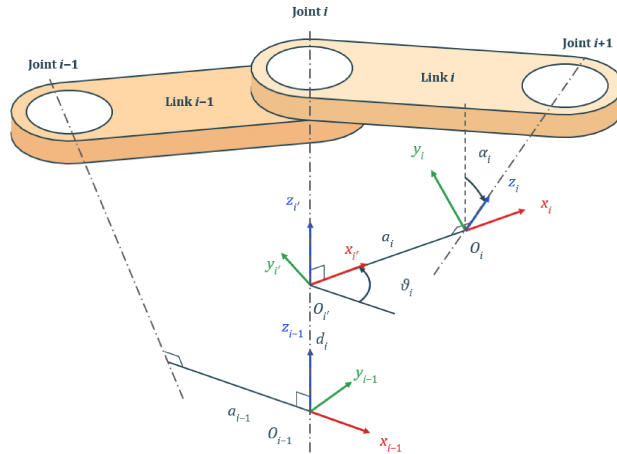


Figure 3.3: Denavit-Hartenberg parameters. Image adapted from [7].

The single transformation then takes the closed form:

$$A_i^{i-1}(q_i) = \begin{bmatrix} c_{\vartheta_i} & -s_{\vartheta_i}c_{\alpha_i} & s_{\vartheta_i}s_{\alpha_i} & a_i c_{\vartheta_i} \\ s_{\vartheta_i} & c_{\vartheta_i}c_{\alpha_i} & -c_{\vartheta_i}s_{\alpha_i} & a_i s_{\vartheta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.8)$$

where c and s abbreviate cosine and sine. The practical procedure consists of numbering the joint axes, assigning the frames, filling a table of the four parameters for each link, building the individual matrices and finally composing them.

3.3.3 Joint Space and Operational Space

The collection of joint variables defines the configuration of the manipulator in the *joint space*, of dimension n . The variables that describe the task, the position and orientation of the end-effector, live instead in the *operational space*, of dimension m .

3.3.4 Kinematic Model of the Human Arm

A common way to describe the human upper limb is as an open kinematic chain made of two rigid segments: the upper arm and the forearm, whose lengths are denoted by $l_{\text{UA}} \in \mathbb{R}_{>0}$ and $l_{\text{FA}} \in \mathbb{R}_{>0}$, respectively. The shoulder model is obtained as the composition of three revolute joints, each associated with one anatomical movement: *shoulder flexion/extension* (SFE), *shoulder adduction/abduction* (SAA), and *shoulder internal/external rotation* (SIER). The elbow, instead, is modelled by a single revolute joint, referred to as *elbow flexion/extension* (EFE) [19]. The resulting kinematic structure is depicted in Fig. 3.4.

The four joint angles, expressed in radians, are grouped in the vector

$$q_h = [q_{\text{SFE}} \quad q_{\text{SAA}} \quad q_{\text{SIER}} \quad q_{\text{EFE}}]^\top \in \mathcal{Q}, \quad (3.9)$$

where $\mathcal{Q} \subset \mathbb{R}^4$ denotes the admissible joint space. This set encodes the physiological range of motion of each joint, which is subject-specific since it depends on both the anthropometry and the clinical condition of the subject [19].

In line with standard robotics practice, the geometry of the chain is described through the Denavit–Hartenberg (DH) convention. The corresponding parameters are reported in Table 3.1.

Table 3.1: Denavit–Hartenberg parameters of the human arm model (standard convention) from [19].

Link	θ_i [rad]	d_i [m]	a_i [m]	α_i [rad]
1	$q_{\text{SFE}} - \pi/2$	0	0	$-\pi/2$
2	$q_{\text{SAA}} - \pi/2$	0	0	$\pi/2$
3	$q_{\text{SIER}} + \pi/2$	0	$-l_{\text{UA}}$	$\pi/2$
4	$q_{\text{EFE}} - \pi/2$	l_{FA}	0	$-\pi/2$

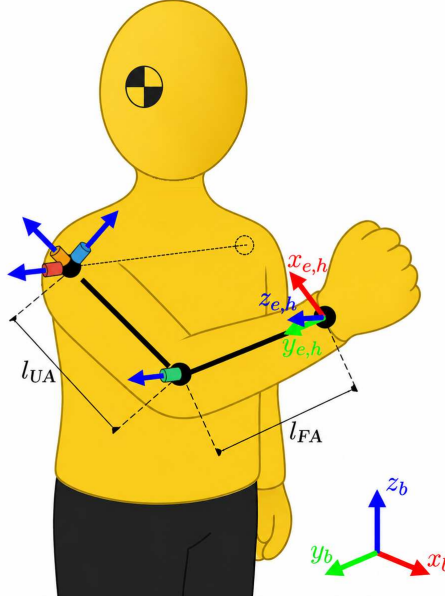


Figure 3.4: Kinematic model of the human arm. The shoulder joints (SFE, SAA, SIER) and the elbow joint (EFE) are shown as red, blue, orange and green cylinders respectively, while the blue arrows indicate the rotation axis of each joint. Adapted from [19].

3.4 Range of Motion as a Kinematic Descriptor

The elementary quantity used throughout the assessment part of this work is the Range of Motion (ROM) of an articular angle. For a given joint angle recorded as a time series during a movement, the ROM is defined as the difference between the maximum and the minimum value reached by that angle over the movement. It summarizes with a number how much a joint has been involved during an exercise: a large ROM indicates that the joint has done a wide angular excursion, a small ROM that it has remained almost still.

The four upper-limb angles considered in this work — SFE, SAA, SIER and EFE — are the ones reconstructed by the inertial motion capture system introduced in Chapter 4. The choice of the ROM as the descriptor of interest has two advantages:

- It is a scalar, and therefore a convenient response variable for the statistical tests used. Each repetition of a movement in each condition returns one ROM value per joint, and the collection of these values across conditions is what the tests analyze.
- It has a clinical meaning, because the amplitude to which a joint can be moved is exactly the kind of information a therapist may look at when judging the mobility of a limb.

3.4.1 Differential Kinematics and the Jacobian

Differential kinematics relates the joint velocities to the linear and angular velocity of the end-effector. Let n be the number of joints of the manipulator, $q \in \mathbb{R}^n$ the vector collecting the joint variables, and $\dot{q} \in \mathbb{R}^n$ the corresponding joint velocities. The motion of the end-effector is described by its linear velocity $\dot{p}_e \in \mathbb{R}^3$ and its angular velocity $\omega_e \in \mathbb{R}^3$, both of which depend linearly on $\dot{q}$:

$$\dot{p}_e = J_P(q) \dot{q}, \quad J_P(q) \in \mathbb{R}^{3 \times n} \quad (3.10)$$

$$\omega_e = J_O(q) \dot{q}, \quad J_O(q) \in \mathbb{R}^{3 \times n} \quad (3.11)$$

Here J_P maps the joint velocities into the translational motion of the end-effector, while J_O maps them into its rotational motion; both matrices depend on the configuration q . Stacking the two relations yields the compact form:

$$v_e = \begin{bmatrix} \dot{p}_e \\ \omega_e \end{bmatrix} = J(q) \dot{q}, \quad v_e \in \mathbb{R}^6, \quad J(q) = \begin{bmatrix} J_P(q) \\ J_O(q) \end{bmatrix} \in \mathbb{R}^{6 \times n} \quad (3.12)$$

This expression is known as the manipulator differential kinematics equation; where v_e groups the linear and angular velocity and $J(q)$ is the geometric Jacobian, a matrix that depends on the manipulator configuration.

3.4.2 Inverse Kinematics

The inverse problem consists of determining the joint variables that produce a prescribed end-effector pose. Its solution is essential because tasks are naturally specified in the operational space; instead, the actuators act in the joint space.

Let $q \in \mathbb{R}^n$ be the vector of joint variables of a manipulator with n degrees of freedom, and let $\mathcal{Q} = \{q \in \mathbb{R}^n : q_{i,m} \leq q_i \leq q_{i,M}, i = 1, \dots, n\}$ be the set of admissible joint configurations, where $q_{i,m}$ and $q_{i,M}$ are the lower and upper limits of the i -th joint. In the operational space, the end-effector pose is described by the vector

$$x_e = \begin{bmatrix} p_e \\ \varphi_e \end{bmatrix} \in \mathbb{R}^m, \quad m \leq n, \quad (3.13)$$

where p_e collects the position coordinates and φ_e is a minimal representation of the orientation (e.g., Euler angles). The direct kinematics equation maps the

joint space into the operational space:

$$x_e = k(q), \quad k : \mathcal{Q} \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m \quad (3.14)$$

where $k(\cdot)$ is a function that is nonlinear in general. Given a desired pose $x_d \in \mathbb{R}^m$, the inverse kinematics problem consists in finding

$$q \in \mathcal{Q} \quad \text{such that} \quad k(q) = x_d \quad (3.15)$$

that is, in solving a system of m nonlinear equations in the n unknowns $q_1, \dots, q_n$.

The inverse problem is harder than the direct one. The equations are nonlinear, so a closed-form solution is not always available; multiple solutions may coexist, such as the elbow-up and elbow-down postures of a planar arm; infinitely many solutions arise for redundant structures; and no admissible solution exists when the wanted pose lies outside the dexterous workspace.

Closed-form solutions can be found through algebraic or geometric approach, and they are guaranteed for a six-degree-of-freedom structure when three consecutive revolute axes intersect at a point or when three consecutive revolute axes are parallel.

When closed-form solutions are unavailable or impractical, numerical techniques based on the Jacobian can be applied to any structure, even if they typically return only one of the admissible solutions.

3.5 Statics and the Kineto-Statics Duality

The Jacobian also describes the relationship between forces and torques in static equilibrium. Applying the principle of virtual work to the manipulator we obtain the following relation:

$$\tau = J^T(q) \gamma_e, \quad (3.16)$$

stating that the joint torques required to balance a generalized force γ_e applied at the end-effector are obtained through the transpose of the geometric Jacobian. This statics relationship, paired with the differential kinematics mapping, expresses the kineto-statics duality.

The range and null spaces of J and J^T together characterize both the velocities the end-effector can attain and the forces the structure can balance. This duality provides a physical interpretation of Jacobian-based inverse kinematics algorithms and a systematic way to transform velocities and forces between coordinate frames.

3.6 Dynamic Modelling

While kinematics ignores the causes of motion, the dynamic model relates the forces and torques acting on the manipulator to the resulting motion to provides

the equations of motion of the structure. A reliable dynamic model is valuable for several reasons:

- The motion of the system can be simulated without recourse to physical hardware;
- It supports the mechanical design of the arm and the sizing of joints, transmissions and actuators;
- It is the foundation on which model-based control laws are built.

Two complementary formulations, described next, are used to derive it.

3.6.1 Lagrange Formulation

The Lagrange formulation derives the equations of motion from energy considerations, independently of the reference frame, once a set of generalized coordinates has been chosen. For an open-chain manipulator the joint variables are used as generalized coordinates. The Lagrangian is defined as the difference between the total kinetic energy and the total potential energy of the system:

$$\mathcal{L} = T - U \quad (3.17)$$

and the equations of motion follow from:

$$\frac{d}{dt} \left(\frac{\partial \mathcal{L}}{\partial \dot{q}_i} \right) - \frac{\partial \mathcal{L}}{\partial q_i} = \xi_i \quad i = 1, \dots, n \quad (3.18)$$

where ξ_i is the generalized force associated with the i -th coordinate. The non-conservative contributions to these generalized forces are the actuator and friction torques and the torques generated at the joints by any contact force exerted by the end-effector on the environment.

The equations of motion can be represented as follows:

$$B(q)\ddot{q} + C(q, \dot{q})\dot{q} + F_v\dot{q} + F_s \operatorname{sgn}(\dot{q}) + g(q) = \tau - J^T(q) h_e. \quad (3.19)$$

where n is the number of joints, $q, \dot{q}, \ddot{q} \in \mathbb{R}^n$ are the joint positions, velocities and accelerations, and $\tau \in \mathbb{R}^n$ is the vector of actuation torques. The matrices $B(q), C(q, \dot{q}) \in \mathbb{R}^{n \times n}$ and the vector $g(q) \in \mathbb{R}^n$ depend on the configuration, while $F_v, F_s \in \mathbb{R}^{n \times n}$ are constant diagonal matrices of the viscous and Coulomb friction coefficients of the joints; the function $\operatorname{sgn}(\dot{q}) \in \mathbb{R}^n$ applies the sign function to each joint velocity. Finally, $J(q) \in \mathbb{R}^{6 \times n}$ is the geometric Jacobian and $h_e \in \mathbb{R}^6$ is the vector of force and moment exerted by the end-effector on the environment, so that $J^T(q) h_e \in \mathbb{R}^n$.

The matrix $B(q)$ is the symmetric, positive-definite, configuration-dependent inertia matrix.

The term $C(q, \dot{q})\dot{q}$ collects the centrifugal and Coriolis effects.

The vector $g(q)$ describes the gravitational torques.

The terms $F_v \dot{q}$ and $F_s \operatorname{sgn}(\dot{q})$ model viscous and Coulomb friction, while $J^T(q) h_e$ shows, through the statics relationship derived earlier, the torques produced by an end-effector contact force.

3.6.2 Newton–Euler Formulation

The Newton–Euler formulation reaches the same equations of motion from a different starting point, based on the balance of all the forces and moments acting on each individual link. The Newton equation governs the translational motion of the centre of mass of a link, while the Euler equation governs its rotational motion.

3.6.3 Direct and Inverse Dynamics

Once the equations of motion are available, two complementary problems can be exploited.

The direct dynamics problem consists of determining the joint accelerations, and by integration the joint velocities and positions, that result from a given set of joint torques and possible end-effector forces, starting from a known initial state. Solving it requires rearranging the model as:

$$\ddot{q} = B^{-1}(q)(\tau - \tau') \quad (3.20)$$

where

$$\tau' = C(q, \dot{q})\dot{q} + F_v \dot{q} + F_s \operatorname{sgn}(\dot{q}) + g(q) + J^T(q) h_e \quad (3.21)$$

gathers all the terms that depend only on position and velocity.

Direct dynamics is the basis of simulation: knowing the state at one instant, the acceleration is computed, and by using a numerical integration technique, one can advance the velocity and position to the next instant.

The inverse dynamics problem consists of determining the joint torques required to produce a desired motion specified in terms of joint accelerations, velocities and positions, by assuming to know any end-effector forces. Inverse dynamics is useful for manipulator trajectory planning and for the implementation of different control algorithms.

Chapter 4

Materials and Tools

4.1 Introduction

This chapter describes the hardware and software tools used in this project: the ROS 2 middleware, the UDP protocol, the Franka Emika Panda collaborative robot, and the Xsens MVN inertial sensors.

4.2 ROS 2

ROS 2 (Robot Operating System 2) is the current, actively developed version of ROS, an open-source ecosystem that supplies the framework, tools, and libraries needed to build, deploy, run, and maintain robotic applications.

ROS is not an operating system in the conventional sense; rather, it is a collection of tools and libraries that lets developers create robots across a range of platforms and programming languages.

At its core there is the framework, which acts as the communication layer connecting the different components of a robot: it manages the exchange of messages, defines standard interfaces, and works with several languages and platforms. This framework is organized with few fundamental building blocks, nodes, interfaces (topics, services, and actions), parameters, and client libraries. Specifically, a node is an independent process that performs a specific task (e.g., reading a sensor, controlling an actuator), while a topic act as a bus for nodes to exchange information.

Around this core, ROS provides a set of tools that make development easier by supporting activities such as building, testing, visualization, and debugging. It also offers ready-made packages covering common functions like navigation, motion planning, manipulation, perception, and simulation.

ROS software is delivered through regularly released versions that bundle a stable release of the core libraries and tools together with many community-contributed

packages. It can run on Ubuntu, Windows, and macOS [14, 15].

4.3 User Datagram Protocol

The User Datagram Protocol (UDP) is one of the two transport-layer protocols defined in the original TCP/IP suite, and it is the simpler [12].

It is situated between the application and the IP layer, acting as an intermediary between the running application programs and the underlying network operations. Like any transport protocol, its main task is to provide process-to-process communication, which UDP accomplishes through port numbers: this allows a message to be addressed not only to a host, but also to a specific process running on that host.

UDP is a connectionless and unreliable protocol, meaning that no connection is set up before or after the transmission; each datagram is handled as an independent unit, carries no sequence number, and may even reach the destination along a different path. UDP offers no flow control and no acknowledgement of received packets, and its only form of error control is an optional checksum: when a non-valid datagram is detected, it is deleted without any communication of this [12].

However, these limitations are the origin of its main advantage. Relying on a fixed 8-byte header and requiring less interaction between sender and receiver than TCP, UDP introduces minimal overhead and delay. For this reason, it is appropriate to processes that exchange short, self-contained messages with little concern for flow and error control, and in particular to real-time applications, where the irregular delays caused by retransmitting lost or damaged data would be more disruptive than the occasional loss of a single message [12].

These same properties make UDP particularly convenient for sensor data. Its low resource usage and fast packet processing allow it to sustain the high data rates produced by devices such as cameras or sensors. Since each datagram travels independently and with no delivery guarantee, packets may occasionally be lost, arrive out of order, or be duplicated; in applications where such faults are rare or where a partial loss can be tolerated, this is an acceptable price for a leaner and faster exchange [13].

4.4 Franka Emika Panda Robot

The Franka Emika Robot is a sensitive robotic arm with seven axes, developed and produced by Franka Emika and operated through a separate control unit. It can handle a payload of up to 3 kg, and every one of its seven joints is fitted with a link-side torque sensor, so the robot is able to sense and react to the forces exchanged with its environment. The arm is meant to be mounted upright and weighs about 17.8 kg [16].

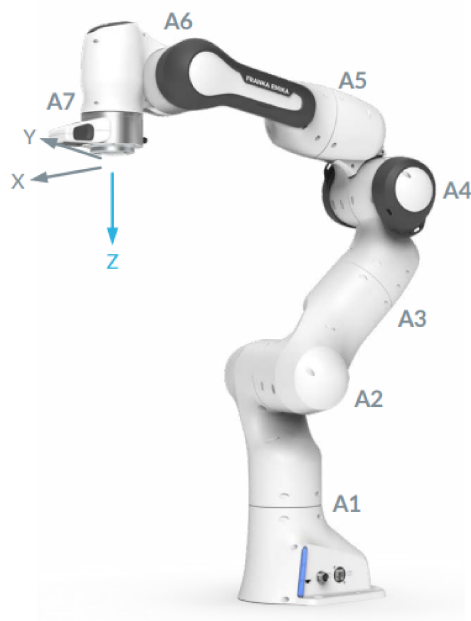


Figure 4.1: The Franka Emika Panda robot [16].

4.4.1 Reachable Space

The working area of the robot is defined by its seven joints and by the travel allowed on each axis. The arm has a maximum reach of 855 mm, measured to the end-effector flange. The range of motion permitted for each joint is summarised in Table 4.1.

Table 4.1: Joint position limits of the Franka Emika Panda [16].

Joint	Range
A1, A3, A5, A7	$-166^\circ / +166^\circ$
A2	$-101^\circ / +101^\circ$
A4	$-176^\circ / -4^\circ$
A6	$-1^\circ / +215^\circ$

From the technical documentation it is also possible to graphically see the reachable space; this space is shown from a side view and a top view in Figure 4.2.

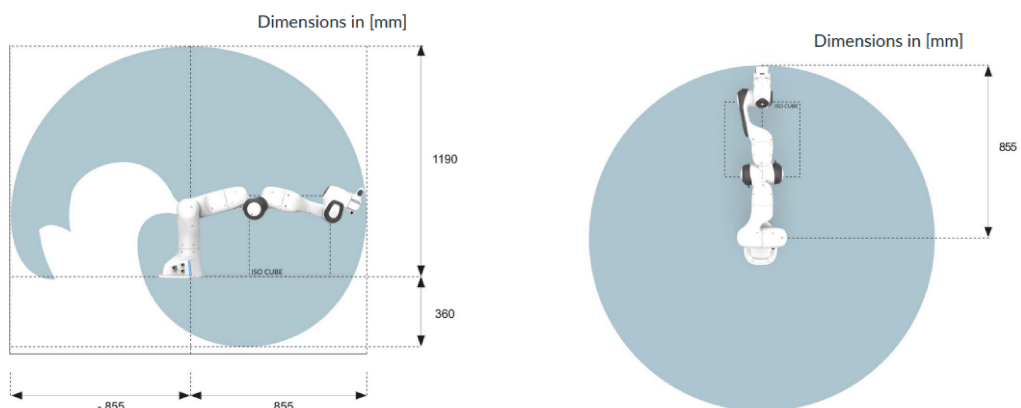


Figure 4.2: Reachable space of the Franka Emika Panda: side view (left) and top view (right) [16].

4.4.2 Kinematic Model (Denavit–Hartenberg Parameters)

The kinematics of the Franka Emika Panda can be described with the modified Denavit–Hartenberg (DH) convention. The robot has seven revolute joints, whose joint variables are denoted by $q_1, \dots, q_7$; an eighth frame is added for the end-effector flange. The kinematic structure of the cobot and parameters reported by Gaz et al. [18] are shown in Table 4.2 and Figure 4.3.

Table 4.2: DH parameters of the Franka Emika Panda [18].

i	ϑ_i	d_i [m]	a_i [m]	α_i [rad]
1	q_1	0.333	0	0
2	q_2	0	0	$-\pi/2$
3	q_3	0.316	0	$\pi/2$
4	q_4	0	0.0825	$\pi/2$
5	q_5	0.384	-0.0825	$-\pi/2$
6	q_6	0	0	$\pi/2$
7	q_7	0	0.088	$\pi/2$
8 (flange)	0	0.107	0	0

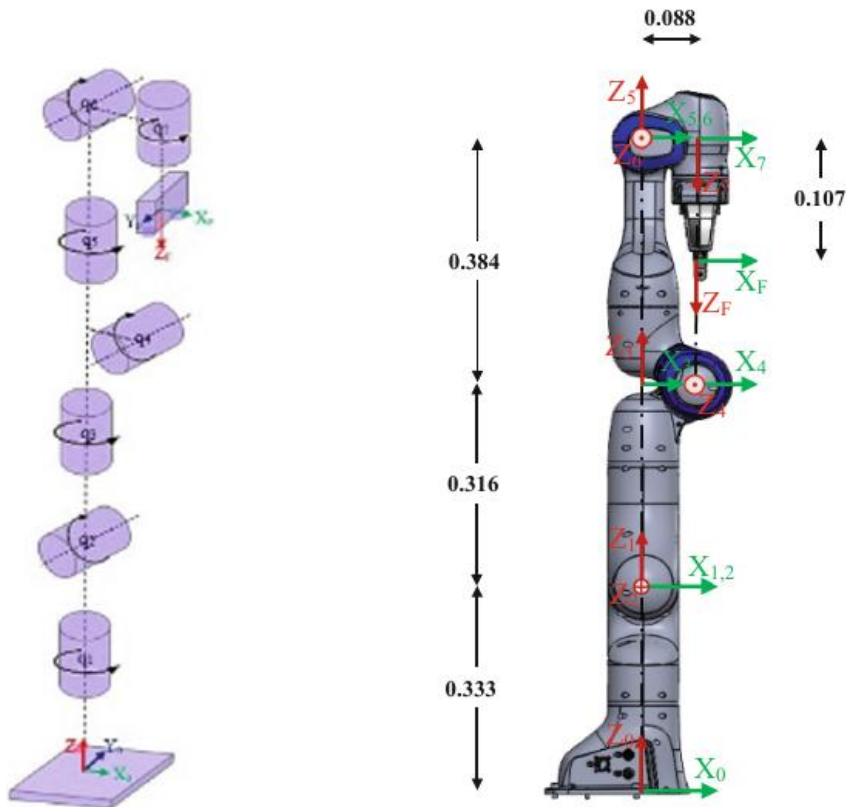


Figure 4.3: Kinematic structure and DH frame assignment of the Franka Emika Panda. Image from [17]; permission requested and granted by the author.

4.4.3 Communication with the Robot (FCI and libfranka)

The Panda is controlled through the Franka Control Interface (FCI), which exchanges data with the user's program via the libfranka library at a rate of 1 kHz. Through this interface the robot streams the measured joint positions q , the joint velocities $\dot{q}$, and the link-side joint torques τ . In addition, the controller evaluates and returns, at the current configuration, several model quantities: the inertia matrix $M(q)$, the gravity vector $g(q)$, the Jacobian $J(q)$, and the Coriolis/centrifugal term $c(q, \dot{q})$.

The robot can be commanded in three main modes:

- torque mode, where the user provides a desired torque τ_d applied to the motors;
- position mode, where a desired joint position q_d is sent;
- velocity mode, where a desired joint velocity $\dot{q}_d$ is sent.

In every mode the FCI controller converts the user's command into the actual motor torque τ_c needed to carry out the task [18].

4.5 MVN Inertial Sensors

For the experiments, the movement of the subject's arm was recorded with the Xsens MTw Awinda [24], a wireless motion capture system made by Xsens. It is a set of small sensors worn on the body, together with a base station that receives their data. Each sensor contains an accelerometer, a gyroscope, a magnetometer and a barometer, and sends its measurements in real time at 60 Hz to the base station, which is connected to the PC by a USB cable. The system uses a Kalman filter to turn these signals into stable joint angles. From these, the arm joint angles are obtained and grouped in a vector q_h described in 3.3.4. The arm is modeled as a kinematic chain with the following degrees of freedom: [19]:

- SFE: *shoulder flexion/extension*
- SAA: *shoulder adduction/abduction*
- SIER: *shoulder internal/external rotation*
- EFE: *elbow flexion/extension*



Figure 4.4: Xsens MTw Awinda inertial motion capture kit, from [31]

4.6 The AS-ULDAR Graphical User Interface

This section describes the software environment within which the whole thesis is developed: the graphical user interface of the AS-ULDAR system (Auto-calibrating System for Upper-Limb Disability Assessment, Neurological and Occupational Rehabilitation). The system is designed to support clinicians in the rehabilitation of the upper limb of subjects affected by neurological conditions such as Parkinson’s disease, amyotrophic lateral sclerosis, stroke and mild cognitive impairment, and it provides both an assessment purpose, by providing accurate measurements of the subject’s kinematics, and a rehabilitation purpose, by adapting the exercises to the subject’s condition.

The description first presents the flexible rehabilitation framework proposed by Alessi et al. [6] and the reason for its architecture, then the robot operational modes, then the structure of the interface, and finally the way the results are computed and visualized. The purpose is to give to the reader a clear picture of the functionalities of the system and illustrate where the contributions of the following chapters fit.

4.6.1 A Flexible Rehabilitation Framework

The AS-ULDAR system is built around a general principle: the rehabilitation logic should be independent of the robot that executes it. To this end the framework is organized into two communicating software components running on ROS 2. One component embeds the robot control interface and is responsible for broadcasting the state of the manipulator, the joint positions and velocities and the pose of the end-effector, and for receiving the control commands; the other is the graphical interface, which allows to program, monitor and analyze the rehabilitation sessions and communicate with the robot control interface through a set of messages. Since only the component that directly communicates with the robot depends on the specific hardware, the interface itself can be reused across different collaborative manipulators, which is what makes the system “flexible” [6].

In the laboratory set-up the framework is coupled with a Franka Emika Panda collaborative robot equipped with a custom end-effector so that the subject can grasp and move it.



Figure 4.5: Emika Panda Robot with customized end-effector

To perform the exercise the robot is put in a gravity-compensated mode, in which it supports its own weight and lets the subject move the end-effector with little effort, while the subject’s own motion is reconstructed by the Xsens inertial motion capture system introduced in Chapter 4. The interface therefore sits at the center of a chain that goes from the sensors worn by the subject, through the reconstruction of the upper-limb kinematics, to the control of the

robot and the storage of the data.

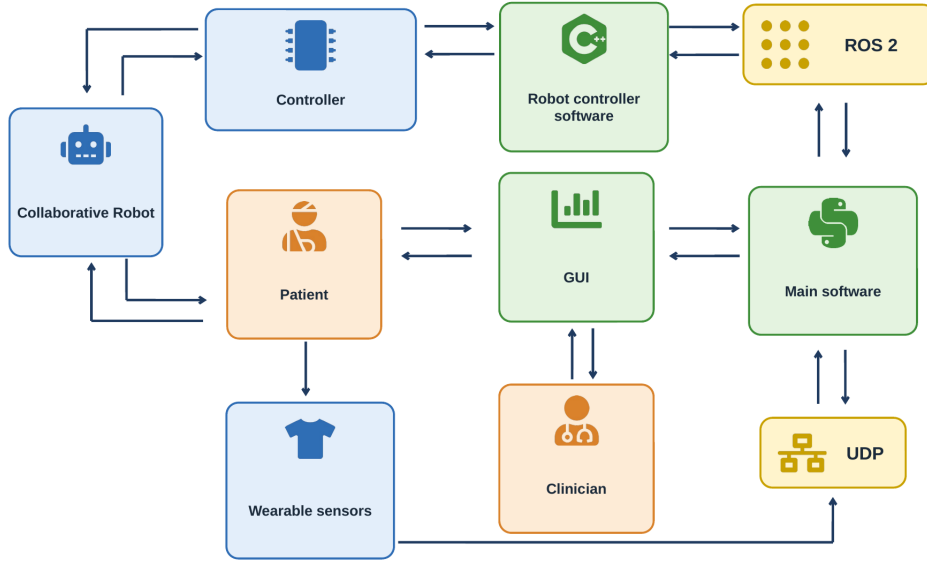


Figure 4.6: System architecture

4.6.2 Modes of Operation

The system offers three modes of operation, each corresponding to a different way of using the robot with the subject. The first is the exercise on which the whole assessment framework of this thesis is based; the other two support a complementary form of training.

The Center-Out Point-To-Point Exercise

In the Center-Out Point-To-Point (CO-PTP) exercise the subject grasps the handle at the end-effector and moves it from a central starting point towards one of a set of targets placed on a circle around that point, and then back to the center.

A complete reaching movement is made of an outward “center-to-target” motion and a return “target-to-center” motion, and the system automatically detects when a movement has been completed and instructs the subject to proceed to the next target. While the subject performs the exercise, kinematic quantities are collected and used to compute the quality metrics discussed below, and a real-time plot shows to the subject the actual path followed, overlapped on the ideal straight lines connecting the center to the targets, so that the exercise provides immediate visual feedback.

The exercise can be delivered in two modes:

- In the traditional mode the subject sees at each step the target to reach, and the current target is highlighted on the screen.

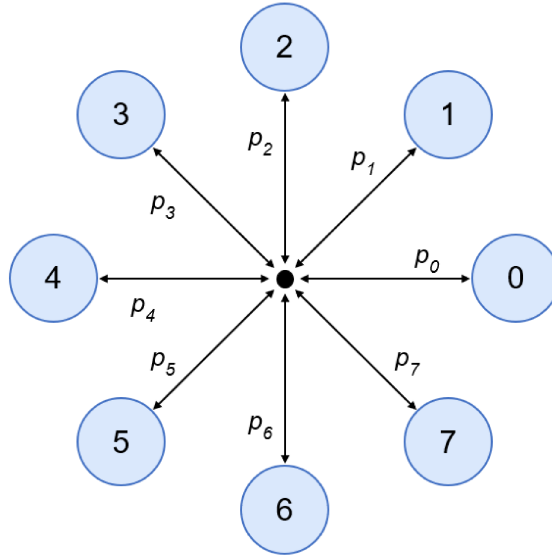


Figure 4.7: The Center-Out Point-To-Point exercise

- In the cognitive mode the subject is first shown a sequence of targets, must memorize and then reproduce it, receiving feedback on whether each movement was directed towards the correct target of the sequence; in this way the same activity provides both physical and cognitive training, which is valuable for subjects whose impairment has a neurological component.

Adaptive Selection of the Targets

A distinctive feature of the exercise, and the one that connects it to the ideas of Chapter 5, is that in the cognitive mode the targets are not selected at random. The probability that a given target is proposed is the sum of two contributions: a uniform component, equal for all targets, and a performance-based component that gives more weight to the directions in which the subject performed worst in the previous session, as measured by the quality metrics.

Trajectory Recording and Trajectory Tracking

The remaining two modes support a guided form of exercise. In the trajectory-recording mode the clinician puts the robot in hand-guidance and moves the end-effector along a desired three-dimensional path, which is stored together with the corresponding joint trajectory. In the trajectory-tracking mode the subject grasps the handle and is guided by the robot along the previously recorded trajectory. These modes are not central to the present work, which focuses on the CO-PTP exercise, but they complete the picture of what the interface offers to the clinician.

4.6.3 Structure of the Interface

From the clinician's point of view the interface is organized into a small number of areas, reachable from a navigation bar at the top of the screen. A subjects-management area lists the subjects registered in the system and allows a new subject to be added, with personal details and the neurological condition; from this list the clinician enters the area dedicated to an individual subject. That area is in turn divided into three sections:

- The details section shows and allows the editing of the data entered when the subject was registered.
- The results section presents the results achieved by the subject.
- The exercise-preparation section lets the clinician set the difficulty of the exercises and start them.

There is also an area dedicated to the recording of trajectories for tracking exercise. All the interface has been implemented by the use of Qt designer.

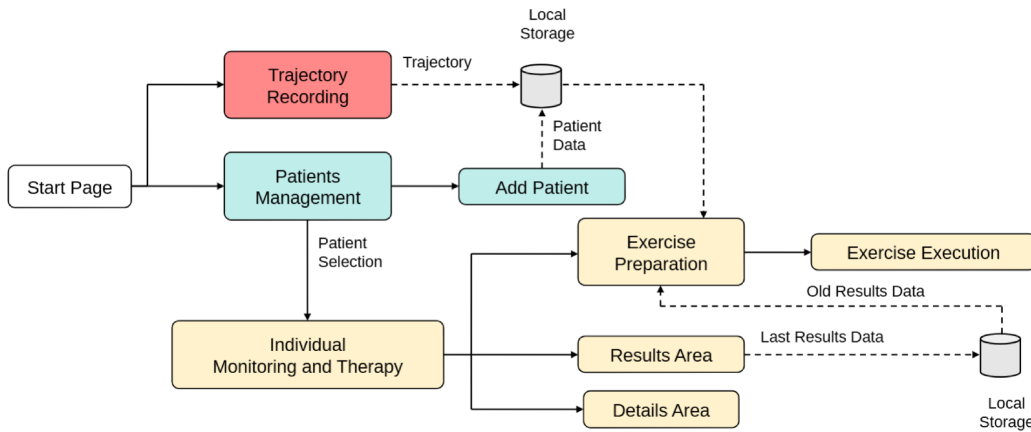


Figure 4.8: Interface structure

4.6.4 Quality Metrics and Results Visualization

The evaluation of the subject is based on a set of quality metrics computed, for each movement direction, from the data collected during the CO-PTP exercise. These metrics include the duration of the movement, its smoothness, the precision error, and the average speed of the end-effector. Such metrics have been shown to correlate with established clinical scales, which is what makes them meaningful as objective descriptors of the subject's condition [6].

The results section presents these metrics in three complementary formats, selectable by the clinician. In the single-session format the values of a chosen metric are displayed on a radar plot, in which each vertex corresponds to one of

the movement directions and the distance of the vertex from the center encodes the value of the metric in that direction.

In the progress format the trend of a chosen metric along a chosen direction is followed across successive sessions, which allows the evolution of a specific difficulty to be monitored over time.

In the statistical comparison format the system checks, across at least three sessions, whether a selected metric differs significantly between sessions.

A Friedman test decides whether any difference exists at all, and, when it does, a Nemenyi post-hoc analysis identifies which sessions differ, the result being displayed as a heat-map whose cells are darkened and annotated with a p-value lower than 0.05 when the difference is significant.

The system therefore already relies on statistical testing to describe the results of the exercise, at the level of the sessions and of the quality metrics. The analysis added in this thesis works in the same way, an overall test to check whether any difference exists, and a post-hoc comparison to say where it lies, but applied to the range of motion of the joints across movement directions.

4.6.5 A Typical Session

A typical session proceeds as follows. Following the system user manual, the clinician first prepares the robot "powering the controller, unlocking the joints and activating the control interface" and then the inertial sensors, which are worn by the subject, calibrated and set to send their data to the interface. The clinician then selects or registers the subject and enters the exercise-preparation section, where the exercise and its parameters are chosen and the exercise is started; the subject performs the CO-PTP until the therapist decides to stop, after which the data of the session are saved into the archive. Over several sessions the results section allows to monitor the evolution of the subject through the radar plots, the progress curves and the statistical comparisons. It is on top of this workflow, and on the data it produces, that the extensions described in the next two chapters operate.

Chapter 5

Statistical Background

5.1 Introduction and Motivation

The goal of the rehabilitation system developed in this work is to monitor and investigate how the range of motion (ROM) varies as a function of the target positions during reaching movements.

Every quantity measured on a human being, and through a chain of sensors, is affected by variability: The same movement, when performed by different individuals, is subject to a certain degree of variability. If this variability is ignored, a difference that is only due to chance can easily be mistaken for a real improvement or a real deterioration, and the clinical conclusion extracted from it will be wrong.

The role of statistics is precisely to separate what is signal from what is noise, and to attach to each conclusion a measure of how much it can be trusted. For this reason, before the software and the experiments are described, it is useful to recall the statistical tools on which part of the system relies.

The presentation is deliberately kept at the level of understanding required to follow the rest of the thesis, focusing on what each test means rather than on how it is derived; the classical text by Montgomery [21] is the main reference for this chapter.

The following sections introduce the logic of hypothesis testing, the elementary quantity used as a response variable, the analysis of variance and the checking of its assumptions, the post-hoc comparisons, and the question of the correct unit of analysis.

5.2 The Logic of Hypothesis Testing

All the tests used in this work share the statistical hypothesis testing logic. One starts by formulating a null hypothesis, which expresses the absence of the

effect under investigation, for instance, that the direction of a movement has no influence on the range of motion of a joint, and an alternative hypothesis, which expresses its presence. The data are then used to decide whether the null hypothesis can be rejected. The decision is never made with certainty: it is always possible to reject a null hypothesis that is in fact true or to fail to reject one that is in fact false.

The tool that quantifies this risk is the p-value, defined as the probability of observing data at least as extreme as those collected, under the assumption that the null hypothesis is true.

A small p-value means that the observed data would be very unlikely if there were no effect and therefore constitutes evidence against the null hypothesis. The threshold below which the null hypothesis is rejected is the significance level, conventionally fixed in advance; for this work it is set to the value of 0.05, so that a result is declared significant when its p-value is smaller than five per cent. It is important to keep in mind that a significant result is a statement about evidence, not a proof, and that its reliability depends on the assumptions of the test being reasonably satisfied and on a proper sample.

5.3 Analysis of Variance

The Analysis of Variance (ANOVA) is a statistical method used to assess whether the mean value of a dependent variable differs significantly across different conditions [21].

The data are organized into groups, one group for each level of the factor, and each group contains the ROM values observed under that level. In ANOVA, a factor is a categorical variable whose effect on the variable of interest is being investigated. Each possible value or category of the factor is referred to as a level. In this work, the direction of the reaching movement is the factor, while each specific movement direction represents a different level of the factor. The null hypothesis states that all the groups share the same mean, that is, that the factor has no effect; the alternative hypothesis states that at least one group mean differs from the others.

This test compares means by looking at variances. The total variability of the data is decomposed into two parts:

- The variability between the groups, which measures how far the group means lie from the overall mean and therefore grows when the factor has an effect;
- The variability within the groups, which measures the residual, unexplained fluctuation of the measurements around their own group mean.

Each of these two quantities provides an estimate of the underlying variability; their ratio, the F statistic, follows a known reference distribution when the null

hypothesis holds. If the factor has no effect, the between-group and within-group estimates are comparable and the ratio is close to one; if the factor has an effect, the between-group term is inflated and the ratio becomes large. An unusually large ratio is therefore evidence against the null hypothesis, and it is translated into the p-value on which the decision is based.

5.3.1 Repeated Measure ANOVA

In its repeated measures form, the same group of individuals is measured under all the conditions (levels) of the study, rather than assigning separate groups to each condition. This design requires fewer participants and removes the need to ensure that different groups are initially equivalent with respect to the dependent [29].

5.4 Checking the Assumptions

The validity of the ANOVA is built on three assumptions.

- The observations must be independent with respect to the others;
- The residual fluctuation within the groups must be approximately normal;
- Its variance of the residuals must be comparable across the groups, a property known as homoscedasticity.

When these conditions are respected, the F statistic behaves as expected and the p-value is trustworthy. When they are seriously violated, the test can become either too liberal, declaring effects that are not there, or too conservative, missing effects that are present.

Independence is the most important assumption and the easiest to violate without realising it; because it has a direct consequence on the way the subject data must be aggregated, it is treated separately in Section 5.5.

5.5 Pseudoreplication and the Unit of Analysis

The independence assumption of the ANOVA deserves particular attention because it is the one most easily violated in a rehabilitation setting. If several repetitions performed by a single subject were treated as if they were independent observations, the apparent amount of information would be artificially inflated: the repetitions share everything that is specific to that individual — the anatomy, the pathology, the level of training — and are therefore correlated rather than independent. This flaw, known as pseudoreplication [22], leads to over-optimistic conclusions and to significant results that would not survive on a genuine sample of different subjects.

Since we compare different directions made by the same subject, we have a correlation between them and we need to use a repeated measure ANOVA, when

the assumption on normality holds (verified with Shapiro-Wilk test); otherwise we have to use a Friedman test with relative post-hoc.

5.6 Post-hoc Comparisons

The omnibus test evaluates whether there is an overall difference among the groups; if it is significant, post-hoc comparisons are performed to identify which groups differ from each other [30]. A significant Omnibus reveals that the factor has an effect, but it does not identify which specific levels differ from which others. Answering this second question requires a post-hoc analysis, that is, a set of pairwise comparisons between the group means. At this point a difficulty arises: performing many comparisons increase the probability of at least one false positive, because each comparison carries its own risk and the risks accumulate. A correct procedure is to control the family-wise error rate, keeping the overall probability of any false discovery at the chosen significance level, rather than controlling the error of each comparison in isolation.

The procedure used in this work is paired t-student if we used repeated measure ANOVA and paired Wilcoxon for Friedman method. They compare all pairs of means simultaneously, using the distribution of the studentized range to set a single critical difference above which a pair is declared significantly different. The p-value was set at 0.05.

Chapter 6

First Contribution: Sensor Communication and Multi-Plane Extension

6.1 Introduction

The chapter 7 and 8 will describe the concrete work carried out on the system. This chapter deals with two aspects that are necessary to make the system usable and testable for the assessment developed in the next chapter, and both were approached by first understanding the existing behavior and then intervening in a controlled way.

6.2 Real-Time Communication over UDP

The inertial motion capture system reconstructs a virtual model of the subject from the signals of the sensors worn on the upper body and streams the resulting kinematic data to the interface in real time. As recalled in Chapter 4, the transport protocol chosen for this kind of exchange is the User Datagram Protocol. Its defining characteristics are a small fixed header, the absence of a connection setup and the lack of retransmission of lost packets; make it lightweight and fast, at the price of not guaranteeing that every packet arrives or that packets arrive in order. For a continuous flow of sensor data this trade-off is exactly the right one: an occasional lost sample is far less harmful than the irregular delay that its retransmission would introduce, and it is therefore preferable to keep the exchange lean and fast.

In the AS-ULDAR set-up the motion capture software is configured to stream its data over this protocol to a fixed address and port on the same machine that runs the interface, as documented in the system user manual. The interface listens on that port, receives the datagrams as they arrive and turns them into the numerical data that the rest of the software can use. The reading of data

transmitted by the sensors was implemented by extending the Python software.

6.3 Extension of the Exercise to Several Working Planes

In its original version of AS-ULDAR, the Center-Out Point-To-Point exercise was used to a single working plane, the horizontal one. Every quantity that describes the position of the end-effector in space, the targets position, the trajectory followed by the subject, the distance from the starting point, the classification of the movement direction and the indication of the current target, was computed by implicitly assuming that the two relevant coordinates were always the ones of the horizontal plane. This assumption constrained the exercise to a single plane and prevented the subject from training on the vertical movements, which may be important in rehabilitation, and which involve the joints in a different way, as later shown in the directional analysis.

The objective of the first development was therefore to make the working plane a choice of the clinician. Three planes are now available: the horizontal plane, kept as the default so that the previous behavior is preserved, and two vertical planes, one sagittal and one frontal.

The change consists in replacing the two fixed coordinates by a pair of coordinates that depend on the selected plane, and in expanding this pair through every part of the exercise that reasons about position. The selected plane is decided in the interface, when the exercise is started, and then transmitted to the component that runs the exercise, which consequently uses the corresponding pair of coordinates everywhere.

6.4 Impact on the Execution and on the Interface

This ampliation of the exercise required modifying both the part of the system that executes the exercise and the part that presents it to the clinician. On the execution side, the computation of the target positions, of the recorded trajectory, of the distance traveled, of the direction classification and of the on-screen marker of the current target were all adapted so that they refer to the pair of coordinates selected for the current plane, in both the traditional and the cognitive modes.

On the interface side, on Qt designer, three radio buttons were added to the exercise-preparation screen so that the clinician can choose the plane;

The selection is read at the moment the exercise is launched and grouped with other execution parameters.

It worth to mention that the horizontal plane coincided with the two coordinates

that were previously assumed, the marker indicating the current target was correct only on that plane and would have been misplaced on the vertical planes; expressing the marker in terms of the selected pair of coordinates corrected this for all planes at once.

The saving of the collected data didn't require any change, because it reads from the trajectory that is now expressed in the correct coordinates according to the selected plane.

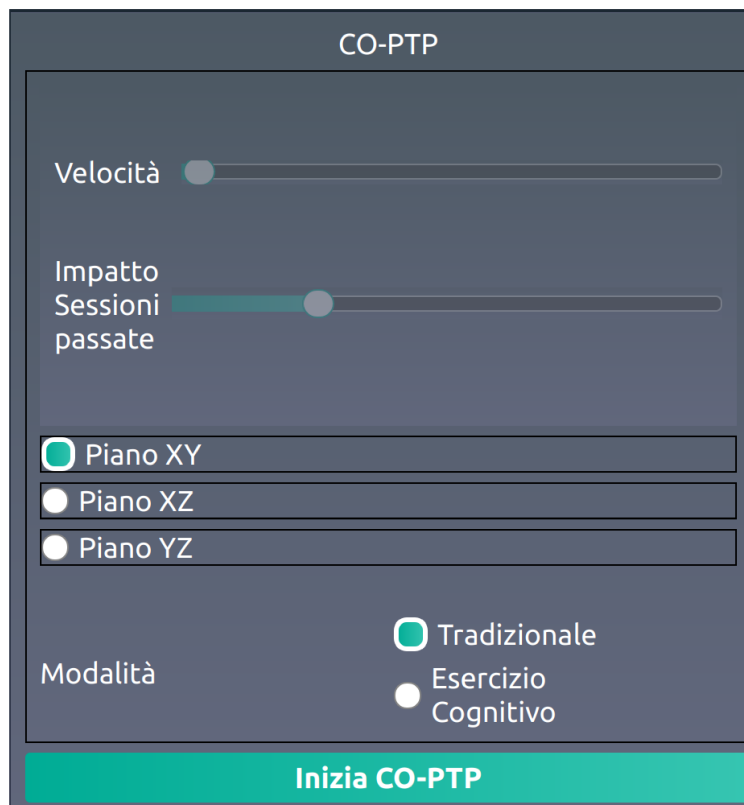


Figure 6.1: The three radio buttons added to the exercise-preparation screen of the GUI for selecting the working plane.

The following table associate the name of a working plane with the corresponding axis.

Table 6.1: Working planes and corresponding axes

working plane	corresponding axes
Horizontal	XY
Sagittal	XZ
Frontal	YZ

6.5 Validation of the Multi-Plane Extension

For each of the three planes an exercise simulation was started in order to verify its validity and feasibility. The reaching movements were reproduced in the PyBullet simulation environment, in which a model of the Franka Emika Panda was moved so as to generate the kinematic data that the exercise needs; the simulated manipulator is shown in Figure 6.2.

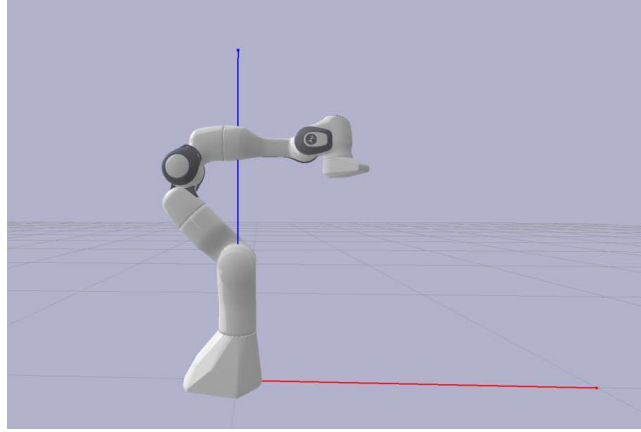


Figure 6.2: The Franka Emika Panda manipulator in the PyBullet simulation environment.

These checks confirmed that the working plane became a parameter of the exercise and built the basis for the directional analysis of the following chapter, which is performed separately on each plane.

6.6 Constraining the Motion to the Working Plane

During the exercise, for each plane, the decision was to physically restrict the robot's movement along the Cartesian axis not belonging to the selected working plane by imposing resistance in those directions.

This offers an advantage regarding the subject's movement, as maintaining a two-dimensional working plane while moving a complex structure like a limb is not always easy; furthermore, it limits the robot's motion, ensuring more precise measurements by keeping it within the correct working plane.

To achieve this, a proportional virtual elastic constraint was applied along the relevant axis to confine movement to the working plane. For example, when the XY plane is the working plane, according to table 6.1, the torque control command is formulated as follows:

$$\tau_{cmd} = g(q) + c(q, \dot{q}) + J^T(q) F_z \quad (6.1)$$

where $J(q) \in \mathbb{R}^{6 \times n}$ represents the analytic jacobian of the end-effector, $g(q) \in \mathbb{R}^n$ is the vector of gravity torques, $c(q, \dot{q}) \in \mathbb{R}^n$ is the vector of Coriolis components, $F_z \in \mathbb{R}^6$ is a constraint wrench defined, for the horizontal plane, in Cartesian space as:

$$F_z = \begin{bmatrix} 0 & 0 & -C(z - z_0) & 0 & 0 & 0 \end{bmatrix}^T \quad (6.2)$$

Where z denotes the current position of the end-effector along the vertical axis, z_0 represents the initial vertical coordinate recorded at the start of the exercise, and $C \in \mathbb{R}$ is a constant proportional stiffness parameter. The term $J^T(q)F_z$ maps the virtual restoring force directly into equivalent joint torques, establishing a virtual planar guide along the XY plane. This mechanism prevents vertical drift without introducing tangential resistance or assistance within the horizontal operational space.

The formulation (6.1) remains unchanged for all three work planes; the only change is the constraint wrench F , which always acts along the Cartesian axis normal to the work plane, leaving all other force components and moments equal to zero.

Thus, to summarize, we have:

Horizontal plane (XY) — constraint along z :

$$F_z = \begin{bmatrix} 0 & 0 & -C(z - z_0) & 0 & 0 & 0 \end{bmatrix}^T \quad (6.3)$$

Sagittal plane (XZ) — constraint along y :

$$F_y = \begin{bmatrix} 0 & -C(y - y_0) & 0 & 0 & 0 & 0 \end{bmatrix}^T \quad (6.4)$$

Frontal plane (YZ) — constraint along x :

$$F_x = \begin{bmatrix} -C(x - x_0) & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \quad (6.5)$$

where x_0 , y_0 , and z_0 are the end-effector coordinates recorded at the start of the exercise, which define the position of the virtual workspace in space.

The following figure virtually illustrates the three work planes for the exercise, also shown to the subjects before the exercises, to clarify the concept of the exercise extending across different planes:

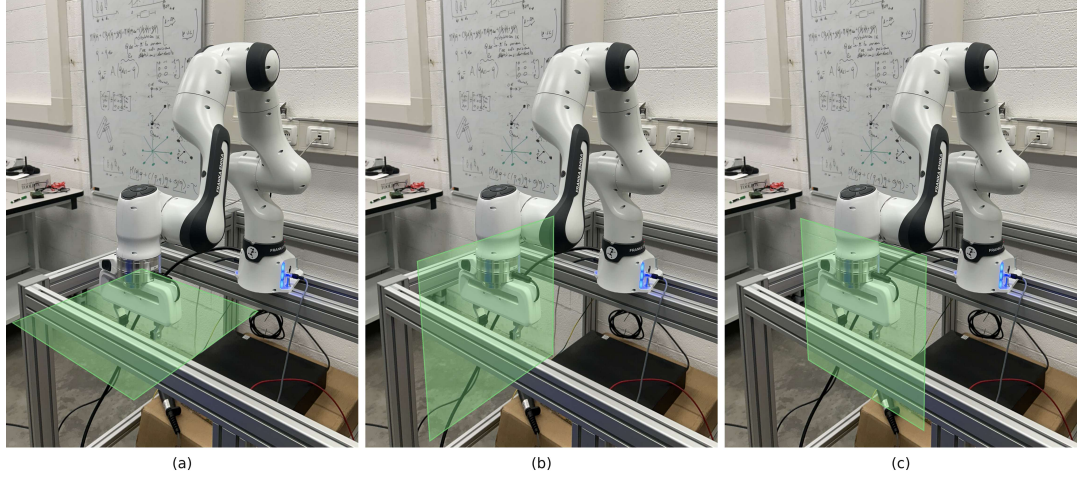


Figure 6.3: Working planes: a) horizontal plane, b) sagittal plane, c) frontal plane.

Chapter 7

Experimental Setup and Data Acquisition

7.1 Introduction

The following chapter first presents how the laboratory test were conducted, illustrating the experimental setup and the data acquisition procedures. In particular, it describes a typical data acquisition session, starting with the parameters required for sensor calibration and concluding with the data acquisition procedure itself.

7.2 Experimental Setup

The experimental setup consists of the Franka Emika robot, secured in place by mounting bars and accompanied by its control station, and a height-adjustable chair positioned exactly 50.8 cm from the lower bracket. This ensures that every test participant performs the exercise under identical conditions;

However, the height of the chair is adjusted for each subject based on their comfort when grasping the robot. The setup is shown in Figure 7.1.



Figure 7.1: Experimental setup.

7.3 Sensor Calibration

For each subject in the table 7.1, measurements were entered into the software; subsequently, 11 sensors were positioned to reconstruct the subjects' upper limbs. Specifically, the sensors were placed as follows:

- 2 sensors on the hands
- 2 on the forearms
- 2 on the upper arms
- 2 on the scapulae
- 1 on the head
- 1 on the sternum
- 1 on the lower back

Figure 7.2 shows their placement.



Figure 7.2: MVN suit configuration; green dots represent sensors placement, from [31].

Once positioned, the setup process, according with the user manual, begins by placing the subject in the N-pose; they then walk, moving their limbs for 3 seconds before oscillating them, for finally returning to the starting position, thereby configuring the sensors.

The program displays whether the configuration has failed, is acceptable, or has succeeded. Testing proceeded only in the last case; otherwise, the calibration was repeated until perfect.

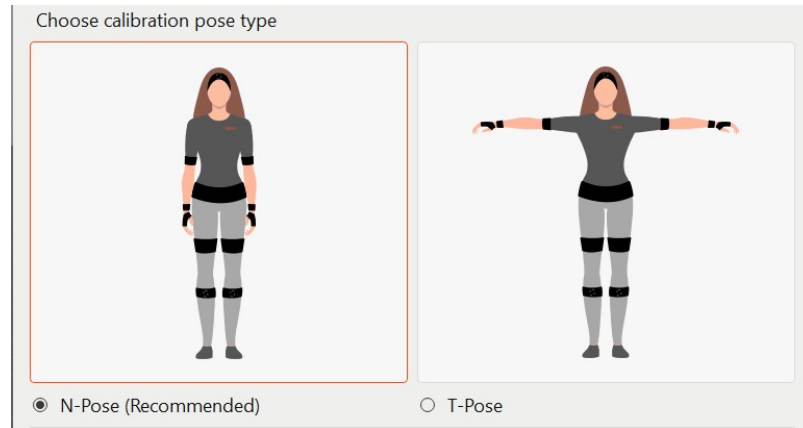


Figure 7.3: MVN configuration poses, from [31].

7.4 Test and data acquisition

Once the sensors were set up, the subject sat in the workstation chair. Each person was briefed on the role of the sensors and the mechanics of the exercise, covering every direction and plane, and was made to understand the importance of using only the arm (avoiding trunk movement, that may lead to compensation movement) and to perform as closely as possible to the indicated directions.

During the exercise, each subject faced a screen displaying the GUI, allowing them to view their movements in real time to better orient themselves.

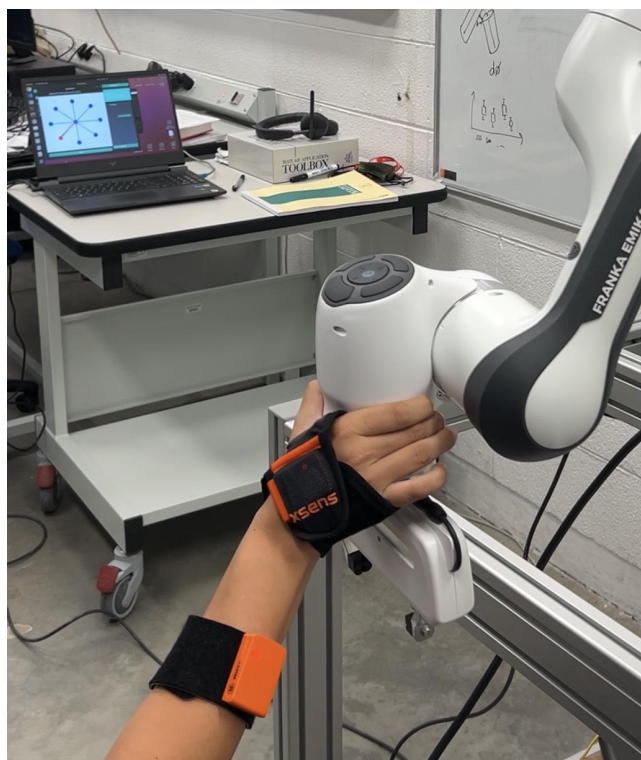


Figure 7.4: Data acquisition, GUI on the upper-left image.

It should be stressed that for each workspace plane, the robot was constrained to movement within that plane by locking the axis not belonging to the exercise's two-dimensional plane, using the control law described in Chapter 7.8.

Throughout the exercise, both the GUI and the sensors were connected to the same port, enabling data acquisition via the previously described UDP protocol.

Once the exercise data for the three planes and twelve subjects had been acquired, we proceeded to analyze them using statistical methods to obtain the results discussed in the next chapter.

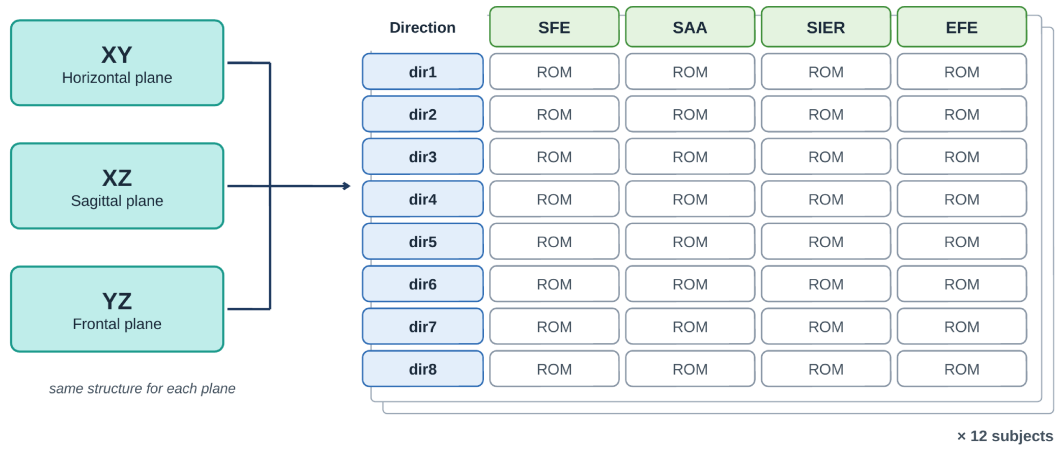


Figure 7.5: Dataset Structure

7.4.1 Subjects Recruiting

Twelve healthy candidates were selected to conduct the tests; healthy individuals were chosen for this stage of development to begin testing the interface and to ensure organizational consistency and data uniformity.

To calibrate the sensors, it was first necessary to measure the height and foot length of each individual in order to insert these measurements into the sensor's software.

Table 7.1: Height and foot length, in cm.

subject	Height (cm)	Foot length (cm)
1	184	31
2	168	31
3	198	32
4	185	29.5
5	170	28.5
6	170	29
7	175	30
8	178	32
9	160	25
10	172	24
11	172	28
12	170	29

Chapter 8

Statistical Assessment of Directional Joints ROM

8.1 Introduction

The final contribution of this thesis is an exploratory data analysis which aims at answering the question: which movement direction recruits a specific human joint the most?

This question is motivated by the ideas presented in the previous chapters: stimulating the most joint demanding movements, testing whether joint recruitment depends on direction, and the platform that records the necessary data;

This chapter is organized as follows: It first states the question precisely; it then describes how the analysis was designed; it then explains how the analysis was brought into the interface, and how the whole assessment was tested in simulation and through laboratory test.

8.2 The Clinical Question

For every working plane and every reaching direction, the exercise records the time evolution of the four upper-limb joint angles, from which the range of motion of each joint is obtained as explained in section 3.4. The question to answer is whether the direction of the movement has a significant effect on the range of motion of each joint, and, if so, which joint is recruited the most in each direction.

The answer is given, for each direction, by the dominant joint, the one whose ROM is largest, accompanied by the result of the statistical test that establishes whether the directional effect is significant at all.

Taken in account all the directions and planes, this answer gives an objective

picture of the directions in which the subject works more and of the joints responsible for that, which is precisely the information needed to steer the exercise towards the most demanding movements.

8.2.1 The Analysis and Its Outputs

An interface for the selection of the plane for the respectively ROM analysis has been implemented with the use of Qt designer, as shown in the following picture:

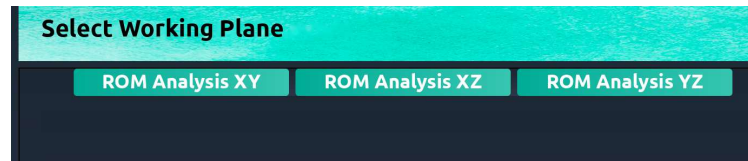


Figure 8.1: Plane selection for ROM analysis.

On these data the pipeline computes the ROM of every repetition, groups the values by direction, as shown in figure 7.5, and runs, for each joint and each plane, the analysis of variance described in Chapter 5.

When the test is significant it proceeds to the post-hoc comparisons, and it identifies, for each joint, the dominant direction in which is used.

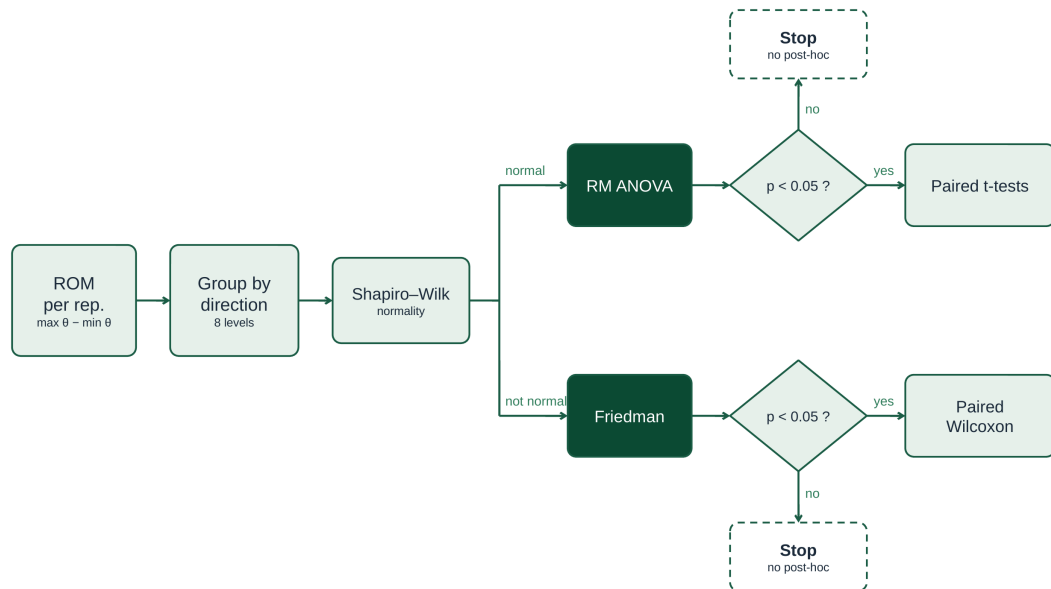


Figure 8.2: Statistical Pipeline

The outcome is then summarized graphically. For each plane a radar plot displays the directional profile of the ROM of the four joints, and a set of bar

charts shows, joint by joint, how the ROM varies across directions; the dominant directions are highlighted and the p-value of the analysis of variance is reported.

A single summary map then reports the dominant joint for every combination of plane and direction. On the simulated data the analysis find the intended pattern, with the joints identified as dominant in exactly the directions in which their amplitude had been made largest, confirming that the pipeline behaves as expected.

8.3 Integration into the Interface

Once validated, the analysis was brought into the AS-ULDAR interface as a dedicated assessment feature, reachable from the navigation menu through its own page. Three radio buttons, once again implemented with Qt designer, are present for starting the analysis; once it is finished the resulting summary figure is displayed, scaled to fit its area. Behind this simple action, the program reads the data collected for all the registered subjects from the folder chosen at first launch, organizes them by plane and direction, runs the same statistical analysis that had been validated in the previous chapter, and produces a single figure that depicts the directional profiles for the selected plane. This GUI component was not designed for clinical use, but rather for research and exploratory analysis.

8.4 Results Presentation

For each work plan, the analysis generates different pictures containing the data needed to answer the questions we posed. The figures are organized as follows:

- A radar plot where the radius represents the mean ROM of each joint in various directions, providing an immediate indication of which joints dominate the plane and in which directions they are most active.
- A box plot for each angle showing the distribution of ROM (median and interquartile range) across subjects in each of the eight working directions, together with a ranking of the directions by mean ROM $\pm$ standard deviation.
- A heatmap displaying the various pairwise comparisons and highlighting significant pairs.

Chapter 9

Results Analysis

9.1 Introduction

The following chapter presents and discuss the results obtained from the analysis depicted in the following chapter.

The aim of this chapter is to understand the behavior of the four analyzed joints in each plane, determining whether the reaching movement affects joint ROM, and identifying which directions are relevant to this effect.

This chapter is divided in sections and each section describe a different plane.

9.2 The Horizontal Plane

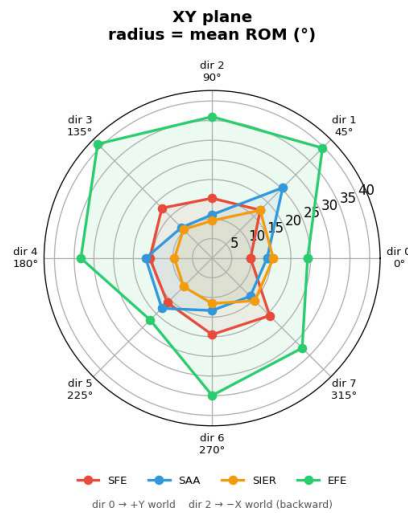


Figure 9.1: XY Plane Radar Plot.

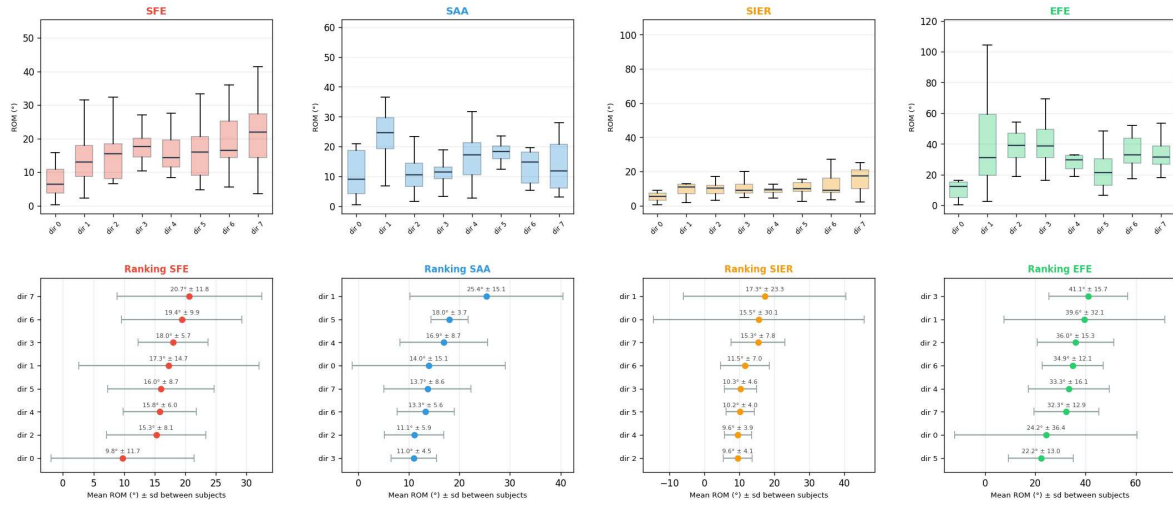


Figure 9.2: Box plot in the upper figure, ranking in the lower part.

In this plane the directional effect observed by data is the weakest. Three of the four joints (SFE, SIER, SAA) do not show a significant dependence of ROM on movement direction. The only joint exhibiting a significant omnibus result is the EFE; however, none of the post-hoc pairwise comparisons are significant, meaning no specific direction stands out in the analysis. This is understandable by looking at Figure 9.3.

The radar plot clearly shows that the EFE is the dominant joint in almost all directions. Shoulder contributions are moderate, which is consistent with a horizontal-plane reaching task, where the hand can be moved more extensively by using the elbow.

In Figure 9.2, the box plots confirm the EFE as the joint with the largest ROM: its medians reach about 30–40° in dir 1–3, 6 and 7, versus roughly 12° in dir 0, while the shoulder joints stay at about 25° or less. The interquartile ranges are wide, and in several directions the distribution is skewed by a few subjects with very large ROM: for the EFE in dir 0, for instance, the mean reported in the ranking is about twice the median. This explains why no pairwise comparison survives the correction, even though some trends are visible, such as the SFE median increasing from dir 0 to dir 7.

The rankings directly answer the question of which directions stimulate each joint the most. Since they are not supported by significant pairwise differences, they should be read as indications rather than proofs; for this reason, a top position is considered more reliable when its standard deviation is small compared to the mean. In the horizontal plane, the EFE is most stimulated in dir 3 ($41.1^\circ \pm 15.7^\circ$) and dir 2 ($36.0^\circ \pm 15.3^\circ$); dir 1 ranks second ($39.6^\circ \pm 32.1^\circ$), but its dispersion is almost as large as the mean, so it is less reliable. The SFE ranks highest in dir 7 and dir 6 ($20.7^\circ \pm 11.8^\circ$ and $19.4^\circ \pm 9.9^\circ$), with dir 3 close behind and more consistent ($18.0^\circ \pm 5.7^\circ$). The SAA is first in dir 1 ($25.4^\circ \pm 15.1^\circ$), that is expected because the target is in a position that force the subject to open

this shoulder joint; while dir 5 ($18.0^\circ \pm 3.7^\circ$) provides a lower but much more repeatable stimulus. For the SIER, the first two positions (dir 1 and dir 0) are driven by a few subjects, as their standard deviations exceed the means; dir 7 ($15.3^\circ \pm 7.8^\circ$) is therefore the most reasonable candidate. Dir 0 is last for the SFE and second to last for the EFE, and where it ranks higher (SIER) its values are not consistent. These directions are the natural starting point for future studies targeting each joint in this plane.

In conclusion, the horizontal plane can be characterized as an elbow-driven plane, with no specific directions proving to be significantly different from others.

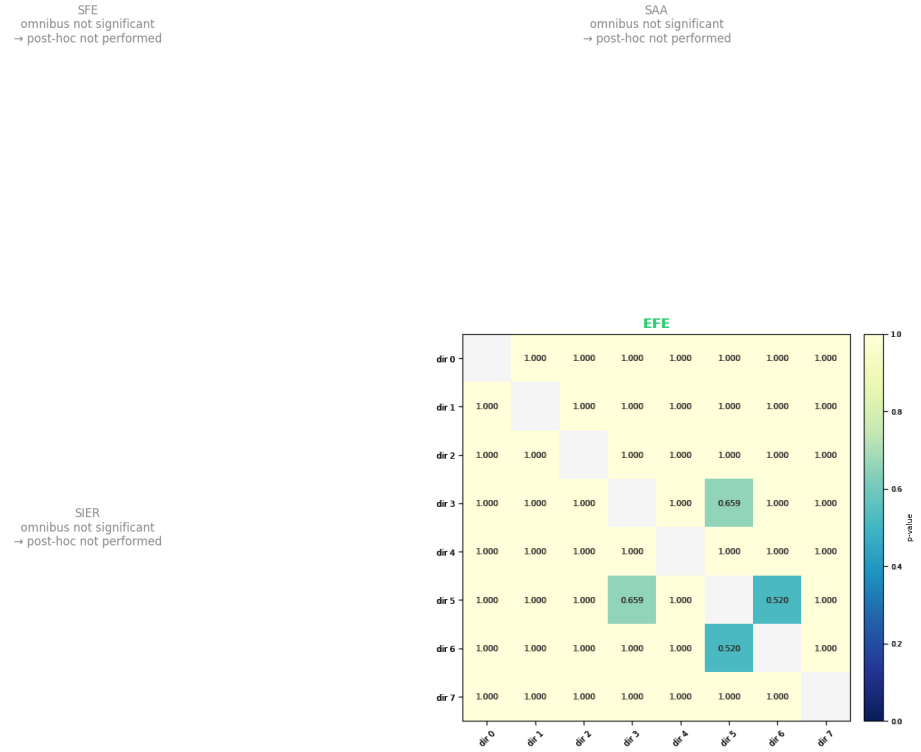


Figure 9.3: XY plane pairwise comparisons. Directions on the axis and p-values inside the cells (cells with red border passed the post-hoc analysis)

9.3 The Sagittal Plane

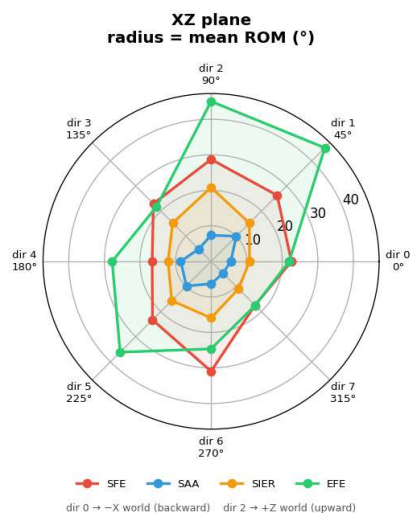


Figure 9.4: XZ Plane Radar Plot.

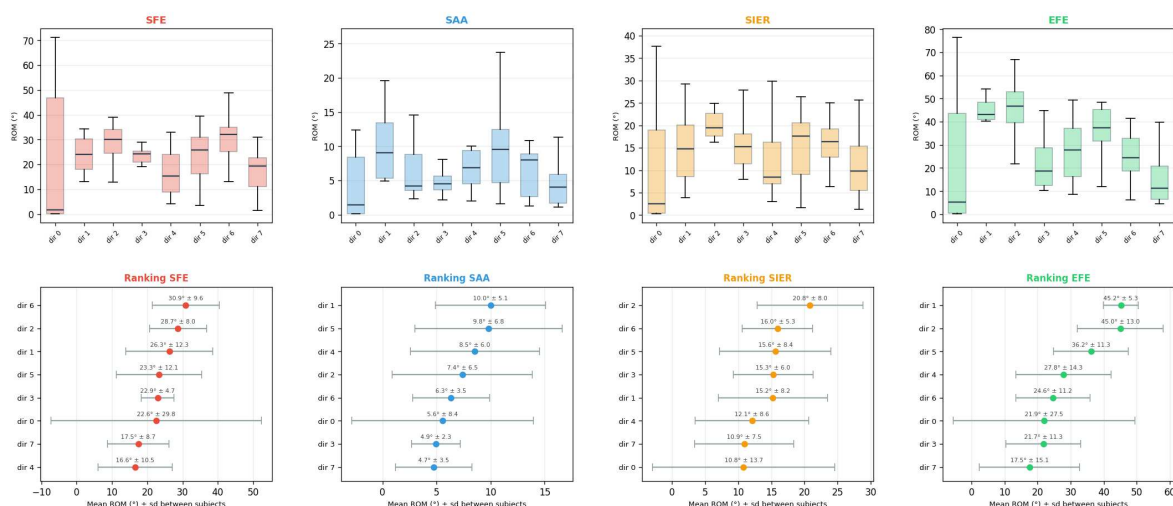


Figure 9.5: Box plot in the upper figure, ranking in the lower part.

In this plane, three of the four joints (SFE, SAA, EFE) reach a significant omnibus level; two of these directions do not remain significant after post-hoc analysis.

In Figure 9.5, the EFE and SFE show the largest ROM. The EFE has the highest medians in dir 1 and dir 2 (about 43° and 47°) and the lowest in the backward directions, with dir 1 also showing a very narrow interquartile range. In dir 0 the distributions of the SFE, SIER and EFE are strongly asymmetric: the SFE median, for instance, is close to 0° while the box extends up to about 47°, meaning that a few subjects with very large ROM inflate the dispersion. This is consistent with the lack of significant post-hoc pairs for the SFE.

In the sagittal plane, the rankings point to dir 1 and dir 2 as the most stimulating directions. The EFE ranks highest in dir 1 ($45.2^\circ \pm 5.3^\circ$) and dir 2 ($45.0^\circ \pm 13.0^\circ$), with dir 1 being the most consistent result in this plane. The SFE is first in dir 6 ($30.9^\circ \pm 9.6^\circ$), followed by dir 2 ($28.7^\circ \pm 8.0^\circ$) and dir 1. The SIER is clearly highest in dir 2 ($20.8^\circ \pm 8.0^\circ$), while the other directions are grouped around 15° or lower. The SAA ranks first in dir 1 and dir 5 ($10.0^\circ \pm 5.1^\circ$ and $9.8^\circ \pm 6.8^\circ$), but its values remain low everywhere, confirming that this plane is not suitable for targeting abduction-adduction. Dir 2 is among the top two directions for three joints (SFE, SIER, EFE), making it the most complete direction in this plane, whereas dir 7 is in the bottom two positions for all four joints.

Once again, the EFE is the dominant joint, and even more markedly so. We observe that the most significant effects occur in the forward and upward directions (dir1, dir2), while they tend to decrease in directions towards the subject. Thus, the forward-upward frontal direction could be used to impose a higher workload on the elbow joint, and direction 6 could be used for the SFE in a potential rehabilitation exercise utilizing the sagittal plane.



Figure 9.6: XZ plane pairwise comparisons. Directions on the axis and p-values inside the cells (cells with red border passed the post-hoc analysis).

9.4 The Frontal Plane

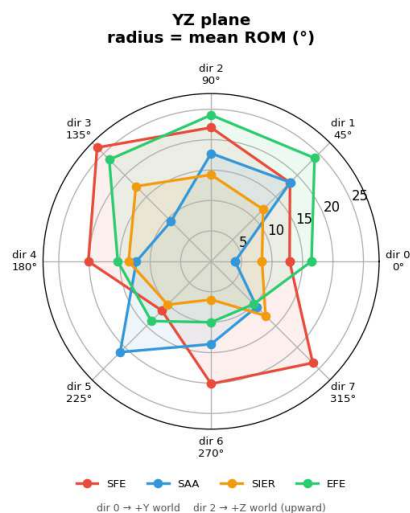


Figure 9.7: YZ Plane Radar Plot.

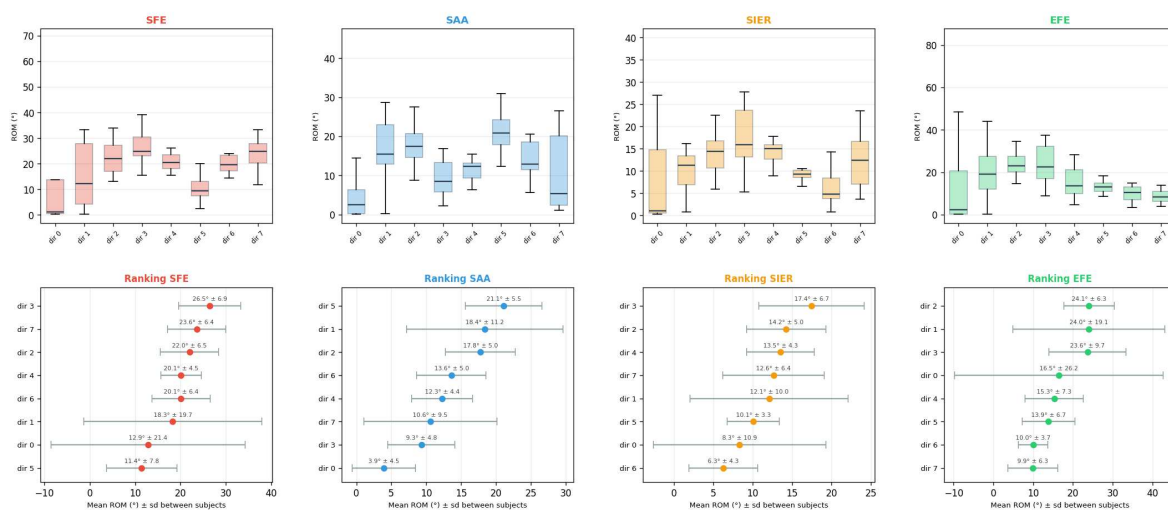


Figure 9.8: Box plot in the upper figure, ranking in the lower part.

In this plane, all four joints are direction-dependent; all omnibus tests are significant, and all post-hoc tests yield significant results.

It can be observed in Figure 9.9 that the SAA shows significant results across all directions. This is expected biomechanically, as lowering and raising the arm in the vertical plane is the type of movement produced by abduction-adduction. We can notice a minimum ROM in direction 0 and a maximum in direction 5. The other three joints also yield significant directional results, and no single joint significantly dominates the others. The radar plot shows that SFE leads in the diagonal directions, while the others are balanced relative to one another.

In Figure 9.8, the medians in the box plots follow the same trends as the means in the rankings, and the ROM varies clearly with direction for all joints. The SAA has the widest range of medians, from about 2.5° in dir 0 to about 21° in dir 5. In most directions the dispersion is moderate; the exceptions are dir 0 and dir 1, together with the SAA in dir 7, where the boxes are much wider because of a few subjects with larger ROM.

In the frontal plane, the rankings agree with the significant post-hoc results and allow a clear direction to be assigned to each joint. For the SAA, dir 5 is confirmed as the most stimulating direction ($21.1^\circ \pm 5.5^\circ$), with dir 1 and dir 2 as alternatives. The SFE and the SIER both rank highest in dir 3 ($26.5^\circ \pm 6.9^\circ$ and $17.4^\circ \pm 6.7^\circ$), with dir 7 as a second option for the SFE ($23.6^\circ \pm 6.4^\circ$) and dir 2 for the SIER ($14.2^\circ \pm 5.0^\circ$). The EFE shows three nearly equal top positions, dir 2, dir 1 and dir 3 (about 24°), among which dir 2 is the most consistent ($24.1^\circ \pm 6.3^\circ$, against $\pm 19.1^\circ$ for dir 1). Dir 2 is in the top three for all four joints, making it the direction that loads the whole arm most evenly, while dir 5 is selective for the SAA, since it ranks last for the SFE and in the lower half for the SIER and the EFE.

In conclusion, the frontal plane yields the richest results, with workloads for the various angles well distributed across the plane and the ranking are consistent with post-hoc.

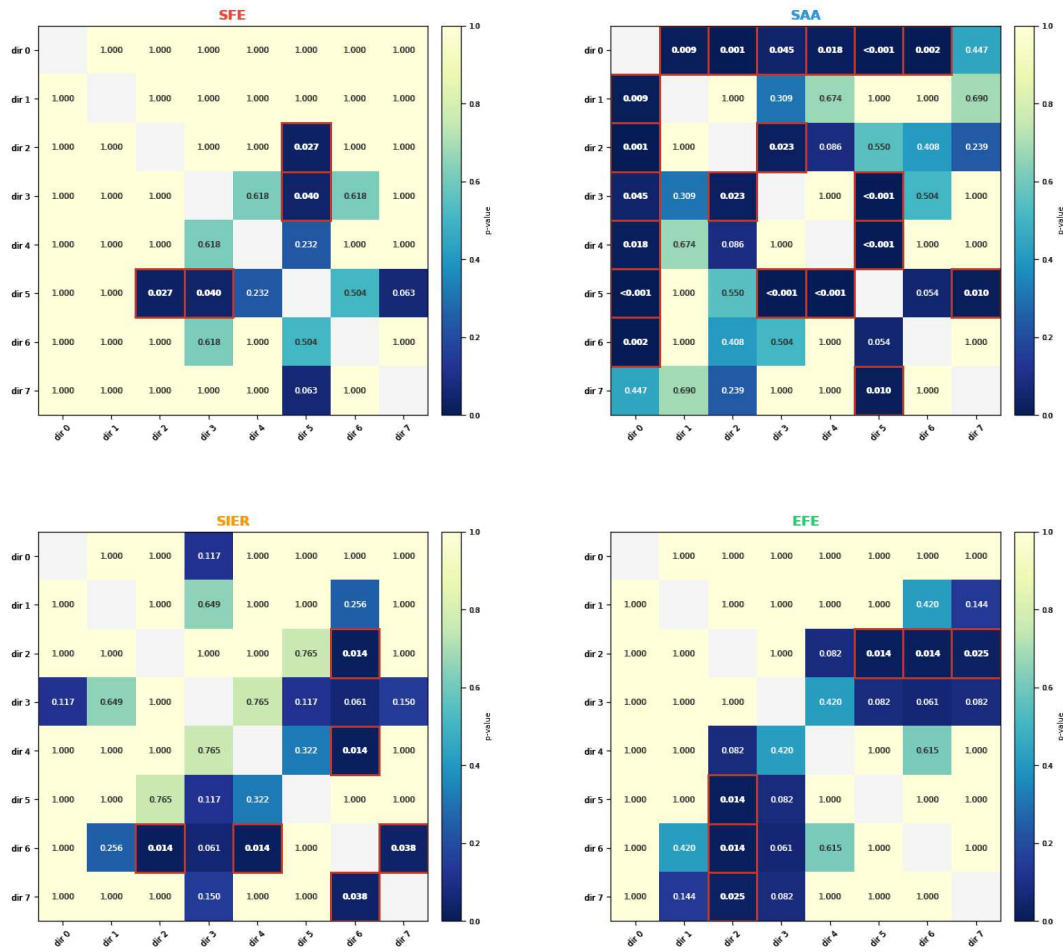


Figure 9.9: YZ plane pairwise comparisons. Directions on the axis and p-values inside the cells (cells with red border passed the post-hoc analysis).

Chapter 10

Conclusions and Thesis Contribution

10.1 Introduction

The following chapter aims to discuss the conclusions of the work presented in this thesis, summarizing the results obtained and addressing their limitations, specifically highlighting the need for testing with larger samples before the work can be extended to clinical use. Subsequently, the contributions of this study will be outlined, tracing the progression from existing literature to the developed solution, and finally considering potential future implementations.

10.2 Conclusions

Based on the results obtained in the previous chapter, we answered the initial research question by identifying trends and a ranking (not yet statistically proven), in which the four joint angles of the subject's upper limb are most utilized, and by determining how the various joints are engaged across different directions and planes.

Starting with a literature review, we identified existing approaches and drew inspiration for our rehabilitation system, subsequently deciding to apply these concepts to our angles of interest and the CO-PTP exercise.

Next, the system structure (originally developed by the Intelligent Robotics Lab research group at the University of Pavia) was modified to operate across three different working planes; this enhancement made the system more complete and versatile, enabling the study of human behaviour in a rehabilitation context within a full three-dimensional space.

Furthermore, a data acquisition and analysis framework was developed and integrated into the user interface to ensure ease of use and an intuitive experience.

Following the disposition of the laboratory experimental setup, data were acquired from 12 subjects across the planes and subsequently analyzed.

An overall assessment of the three planes reveals a consistent and interpretable pattern; the effect of movement direction on joint angles intensifies with the vertical components of the plane. The number of significant directions increases from zero in the horizontal plane to three and then four in the two planes involving vertical movement. Indeed, movements requiring arm elevation demand greater effort to counteract gravity, a finding consistent with our analysis.

Each plane features a “natural driving joint”, the dominant articulation whose anatomical movement aligns with the plane’s geometry: the elbow serves as the driving joint in the horizontal plane (and in directions where reaching the target relies heavily on elbow movement), while shoulder movements dominate the frontal plane, where the arm is raised and lowered relative to the shoulder. This correspondence is consistent with the anatomical movements expected in a healthy subject.

10.3 Limitations

For nearly all 12 subjects, this was their first interaction with a robot and this specific exercise. Since the exercise and the movement of the robotic arm are not immediately intuitive or simple, the data must be interpreted with this statement in mind. Consideration must also be given to the possibility that, once familiar with the exercise, a subject might adopt a movement pattern that is personally comfortable rather than anatomically natural.

The most important limitation is that the statistical power of this test is limited by the small sample size, and data from a couple of subjects were excluded in certain planes due to outlier movements.

The section on future work will address these limitations, which arose from applying a theoretical concept to real-world conditions and the resources available at the time.

10.4 Thesis Contribution

Table 10.1 summarizes the contribution of this thesis with respect to what was already available. The table has two columns: the left one lists the elements that existed before this work, contains the ideas taken from the literature (Zolotas et al. [23] and Kikuchi et al. [20]), the CO-PTP exercise with its gravity-compensated control, and the statistical analysis and the directional analysis performed on the horizontal plane only. The right column reports, row by row, what this thesis adds to each of them. The first rows concern the transposition of the two literature ideas to the CO-PTP exercise and to the four upper-limb joints, and the extension of the exercise from the horizontal plane

to three working planes (XY, XZ, YZ), together with the plane selection in the GUI and the planar constraint control law. The last rows concern the analysis of the results: the statistical evaluation of the directional joint ROM and the directional characterisation of the three planes.

Table 10.1: Thesis Contribution.

Already available	Contribution of this thesis
Productive inconvenience: a robot that stimulates varied postures during handovers instead of minimising the receiver's effort (Zolotas et al. [23])	Principle adopted to motivate the identification of the movement directions that demand more of specific joints in the CO-PTP exercise
Direction-dependent joint demand, tested with an ANOVA of the range of motion across reaching directions (Kikuchi et al. [20])	Idea and method transposed to the CO-PTP exercise and to the four upper-limb joints supported by the system
CO-PTP exercise on the horizontal plane	CO-PTP exercise on three working planes (XY, XZ, YZ)
—	Plane selection in the GUI
Gravity-compensated control	Planar constraint control law
Statistical comparison of the quality metrics across sessions, on the horizontal plane only (Alessi et al. [6])	Statistical evaluation of the directional joint ROM on the three working planes (XY, XZ, YZ)
Directional analysis on the horizontal plane only (Kikuchi et al.)	Directional characterisation of the three planes

10.5 Future Work

A possible idea for future work would be to extend the test to a larger sample of healthy subjects in order to achieve greater statistical power, thereby allowing the results to be compared with those obtained in the current study.

With a more comprehensive understanding of the situation, a control law could be developed to enable the robot to pass objects in directions that specifically require greater use of certain joints.

With a more comprehensive understanding of the situation, a control law could be developed to exploit the directions that specifically require greater use of certain joints. Two contexts are possible. In a handover scenario, the robot could pass objects to the subject in those directions. In the CO-PTP exercise,

the targets could instead be proposed more often in those directions, extending the adaptive target selection already present in the system [6].

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