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A CASE-STUDY VISION

Real-time Teleoperation of a Humanoid Robot (avatar) with the Motion Capture System Perception Neuron

Teleoperación en tiempo real de un robot humanoide (avatar) con el Sistema de Captura de Movimiento Perception Neuron

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ABSTRACT

This research describes a real-time teleoperation system for a NAO humanoid robot, visualized in a virtual environment, using an inertial motion capture system known commercially as Perception Neuron. To achieve this goal, the data captured by the MoCap system hardware is transmitted to the Axis Neuron software, where a model of the human skeleton will be automatically generated and each frame of movement will be captured, then all the captured data will be transmitted from this software to another computer with ROS, using a TCP/IP communication protocol, with insignificant latency. In Rviz (ROS - 3D visualization tool) the virtual model of the NAO robot will be observed. As a result, one-way teleoperation was achieved with an acceptable imitation of the movements performed by the non-technical operator. These routines involved different joint segments of the arms, legs and head. The results are promising to advance in the implementation and strengthening of this system with a therapeutic purpose, given that the NAO robot is considered a Social Assistance Robot, a recent field of study that is interested in the use of this and other robotic platforms in rehabilitation therapies.

RESUMEN

En esta investigación se describe un sistema de teleoperación en tiempo real de un robot humanoide NAO, visualizado en un entorno virtual utilizando un sistema de captura de movimiento inercial conocido comercialmente como Perception Neuron. Para alcanzar este objetivo, los datos capturados por el hardware del sistema MoCap son transmitidos al software Axis Neuron donde se generará automáticamente un modelo del esqueleto humano y se capturará cada cuadro de movimiento, enseguida se transmiten todos los datos capturados desde este software hasta otro computador con ROS utilizando un protocolo de comunicación

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TCP/IP con una latencia poco significativa. En Rviz (una herramienta de visualización 3D de ROS) se observa un modelo virtual del robot NAO. Como resultado, se logró una teleoperación unidireccional con una imitación aceptable de los movimientos realizados por un operador no-técnico. Estas rutinas involucraban diferentes segmentos articulares de los brazos, las piernas y la cabeza. Los resultados son prometedores para avanzar en la implementación y fortalecimiento de este sistema con un propósito terapéutico, dado que el robot NAO se considera un Robot de Asistencia Social, un campo de estudio reciente que se interesa por el uso de esta y otras plataformas robóticas en terapias de rehabilitación.

1. Introduction

The first robotic systems that were designed focused on industrial applications that did not involve interactions between human users and robots. These systems were designed to achieve efficient and optimal performance of a specific task [1]. However, a new field of research emerged that focuses on the design, implementation, and evaluation of robotic systems that interact with humans. This *human-centered design,* as noted by (Burke et al. 2010) cited in [1], makes Human-Robot Interaction (HRI) a unique multidisciplinary field that requires expertise in computer science, engineering, psychology, social and behavioral sciences, anthropology, philosophy, and ethics [1].

Robotics in rehabilitation has always had two main objectives: (1) Designing robots that provide safe physical interaction, and (2) Designing robots that engage in socially comprehensible and acceptable interactions for the user [1]. In this regard, Socially Assistive Robots (SAR) represent the best of the fusion between engineering and rehabilitation medicine for addressing the educational, socio-emotional, cognitive, sensory, and motor needs of children with disabilities, paraphrasing Shic & Goodwin, 2015, as cited in [2]. SAR can be considered as robotic technology in rehabilitation, and the most popular method for evaluating any rehabilitation platform (to determine whether these systems have been effectively used in rehabilitation interventions for the intended population) has been through interviews and questionnaires as a quick way to gather information on the adoption and acceptance of the technology by users [1]. This is where the study of human body kinematics becomes an area of interest in biomedical engineering, biomechanics, sports science, and especially in the field of rehabilitation, with applications such as the study of the effect of age on the human body [3].

Ideally, the use of a robotic system in rehabilitation should not require an expert operator or complex training for its operation [1]. In this regard, [4] concluded, among other things, that the configuration of a socially assistive robot (in this case, a NAO robot) used for rehabilitation should be possible without the help of engineers, who also need training in handling the robot's native software or obtaining specialized technical knowledge when it is desired that the humanoid robot executes complex instructions [5]. Ultimately, the goal is for therapy sessions to be easily configured by the therapist, caregiver, or educator. In conclusion, teleoperation with humanoid robots involves integrating human cognitive, physical, and social skills with the physical capabilities of humanoid robots [6].

However, humanoid robots present interdisciplinary and multidisciplinary challenges for teleoperation, ranging from kinematics, dynamics, and control to communication and human psychophysiology. Due to their human-like appearance, expectations are high: these robots are expected to be friendly, socially interactive, and behave naturally [6]. Imitating human movement is perhaps the simplest way to operate a humanoid robot [5]. Nevertheless, several challenges exist, including motion data collection, physical differences, the number of degrees of freedom, and dynamic disparities. Thus, the field of teleoperation is considered a global challenge [6].

This research involves unidirectional teleoperation of a social assistance robot without requiring an expert user for the execution of simple or complex movements, with the expectation that it will lay the groundwork for a comprehensive rehabilitation solution that could eventually be validated by therapists or users interested in such tools.

2. Research Context

This section presents an overview of three theoretical-conceptual axes that will frame the current research.

2.1. Motion Capture Systems

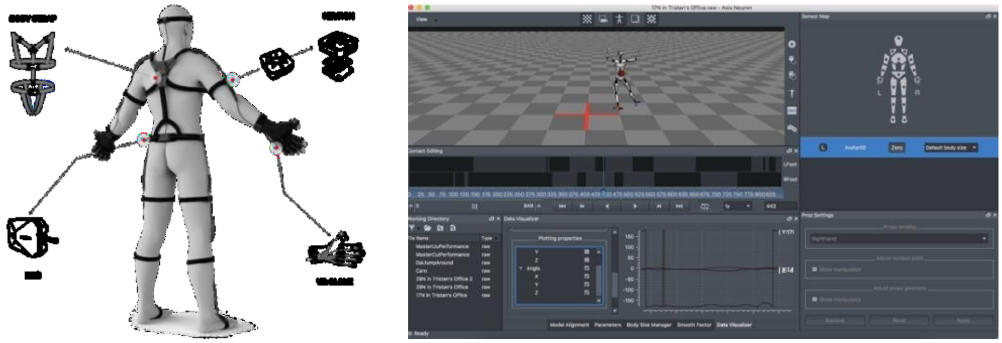
Movement is intrinsic to all complex organisms. It allows them to adapt to or respond to changes in their environment [7]. In fact, movement itself is a complex task influenced by internal factors such as weight, injuries, skeleton, musculature, emotions, among others, and external factors like gravity, footwear, environment, clothing, and more. However, internal factors have been the focus of various studies, leading to significant advances in the field, as studying movement requires capturing it first [7]. Generally, motion capture systems consist of specialized hardware and software for data processing [8]. However, these developments, with their varied purposes, have strengths and weaknesses as noted by [9], as shown below: (Table 1).

On the other hand, *motion capture systems should be selected according to their application* [7]. If the research focuses on biomechanics, telerehabilitation, or less complex rehabilitation applications, technologies like markerless and easily accessible Kinect systems can be used. For research requiring unrestricted movement, inertial and magnetic systems are the best option [9]. Perception Neuron 2.0 (Figure 1) is an inertial motion capture system manufactured and distributed by Noitom Limited, which can be used in various types of applications, including real-time [10].

Table 1. Characteristics of Motion Capture Systems [9].

Type of technology	Strengths	Weaknesses
Optical systems with markers (Leading systems: Vicon and BTS)	Precision Data processing 3D animation Virtual and augmented reality: Covers a wide range of applications High-complexity studies	Space and system setup time Equipment cost Robust system Marker occlusion Sports studies Delimited space
Markerless optical systems (Leading system: Kinect)	Cost Easy manipulation Data processing Precision in spatiotemporal parameters Telerehabilitation	Precision in angular parameters High-complexity studies
IMU and magnetic systems	Sports studies Portability Easy manipulation Conducting studies Outside the laboratory Equipment cost	Precision High-complexity studies

Figure 1. Perception Neuron 2.0 Motion Capture System [10].



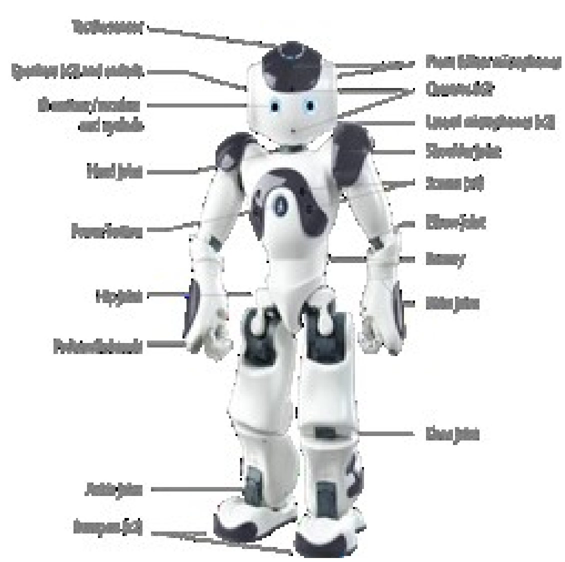
2.2. Robotics in Rehabilitation

Robotics in rehabilitation is considered *an emerging technology for the diagnosis and treatment of various types of physical and mental disabilities* [11]. A classic example is smart powered wheelchairs, which allow users to select local destinations and feature an automatic navigation system [11]. Three main branches of rehabilitation robotics have been identified: *Assistive Robotics* (AR), which aims to replace or compensate for the lack of motor and/or sensory skills, as defined by Feil-Seifer & Mataric in 2005, as cited in [11]; *Socially Interactive Robotics* (SIR), which primarily deals with human behavior when interacting with a robotic companion that can speak and exhibit gestures, a term introduced by Fong, Nourbakhsh & Dautenhahn in 2003, according to [11]; and finally, *Social Assistive Robotics* (SAR), recently defined as an area of study representing the intersection between SIR and AR [11]. The goal of a Social Assistive Robot (SAR) is *to create a close and effective interaction with a human user to provide assistance and measure progress in recovery, rehabilitation, learning, etc.* [2]. Specifically, SARs are considered potentially valuable as therapeutic intervention tools for children with disabilities [11].

2.2.1. NAO robot

It is a programmable social humanoid robot (Figure 2) developed by Aldebaran, formerly known as SoftBank Robotics Europe, now a partner of the German group United Robotics. It is used in rehabilitation engineering as a Social Assistive Robot (SAR) [4]. The robot stands 58 cm tall and weighs 5.5 kg. It can be powered either via a cable or by lithium-ion batteries. It has network access via Ethernet or Wi-Fi [12]. Additionally, according to [12], it features a total of 25 degrees of freedom (DOF): 2 DOF in the head, 5 DOF in each arm, 1 DOF in the pelvis, 5 DOF in each leg, and 2 DOF in each hand; the joints are driven by MAXON DC motors. The NAO robot provides a comprehensive set of sensors, cameras, and microphones that enhance its autonomous capabilities, along with interactive mechanisms that facilitate social interaction with people [4].

Figure 2. NAO robot [13].



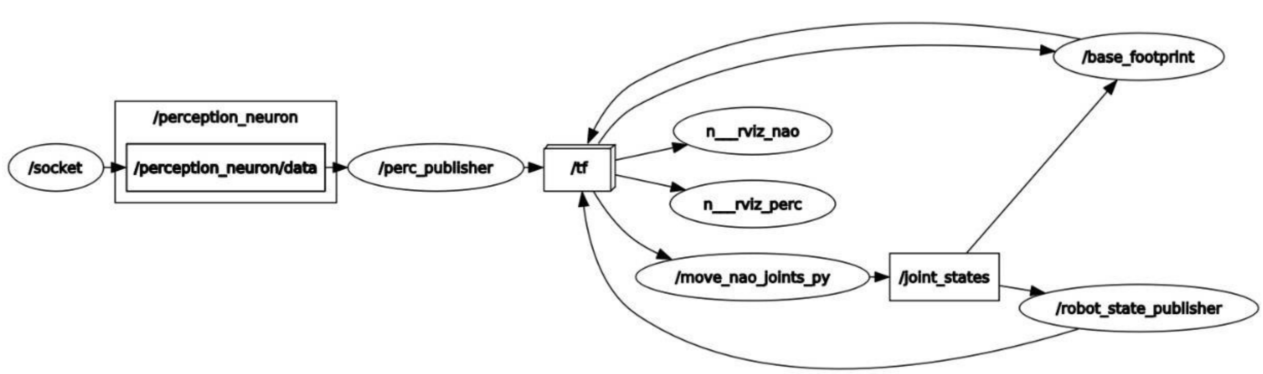
3. Methodology

To begin, the human instructor uses the Perception Neuron suit with 19 sensors (neurons) that record their movements through IMU sensors. These data are captured with the help of the software provided with the hardware, called Axis Neuron, also developed by Noitom Limited, which runs on the Windows operating system. The software continuously reconstructs the human skeleton model in real time. Each frame of captured movement is stored in BVH file format, originally developed by Biovision, which provides information about the hierarchical structure of the human skeleton model [14]. The BVH data is translated into a data matrix that can be sent to ROS via the PerceptionNeuronROSserial application on Windows. This application, a prior development (available online), facilitates the transmission of Perception Neuron motion data through Axis Neuron to ROS. It was last updated in 2017 by Björn Lütjens with his project Real-Time Teleoperation of Industrial Robots with the Motion Capture System Perception Neuron from the Technical University of Munich [15], who is currently a Ph.D. candidate at the Massachusetts Institute of Technology (MIT). His update allowed for a higher transmission rate and the ability to transmit the entire skeleton model, rather than just a section as originally developed by Simon Haller from the University of Innsbruck [16]. The latest update ensures the transmission of all data captured by the MoCap inertial system's sensors, enabling future and diverse applications in robotics using ROS.

The connection between Windows and ROS is established through a client-server architecture using the TCP/IP communication protocol. In ROS (Figure 3), the */socket* node acts as the receiver of information transmitted from Axis Neuron. This node publishes the data to the*/perception_neuron/data* communication topic, to which the */perc_publisher* node subscribes. The */perc_publisher* node performs operations to determine how the reference frames of the human skeleton transmitted from Axis Neuron should be moved and then publishes this data to */tf*. In */tf*, users can track multiple reference frames and access all the movement data of the skeleton. The */move_nao_joints_py* node (developed by the authors of this research) processes the received data to control the movement of the robot's joints through the*/joint_states* communication topic.

Specifically, to achieve the movement of the NAO robot's arms, an inverse kinematics solution was found, while the movement of the robot's legs and

Figure 3. ROS rqt_graph, nodes and topics of the program.



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head is achieved through a *one-to-one* relationship with the joints. Finally, in Rviz, a 3D visualization tool in ROS, the human skeleton model and the robot model can be viewed side by side. The NAO robot is fully modeled and set up in ROS for visualization and analysis; this virtual model was last updated in 2019, originally developed by the Humanoid Robots Lab at the University of Freiburg and Arming

Hornung. It essentially provides a set of functions for the NAO robot in a virtual environment (stability and positioning in space, sound localization, text-to-speech synthesis, computer vision, among others) and allows visualization of versions 1.14 and 2.1 of the NaoQI API by Aldebaran, the manufacturers and distributors of NAO [17].

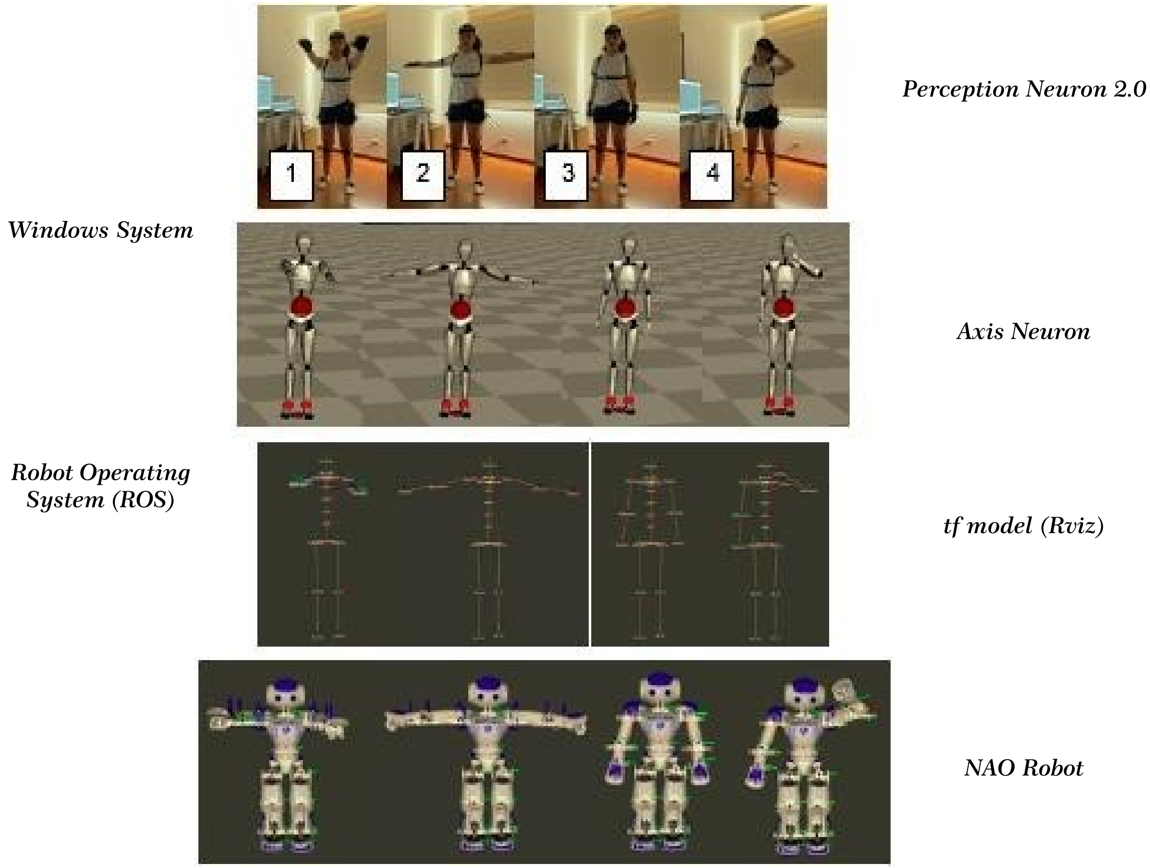
4. Results

The system was tested for 30 minutes, with breaks of 2-5 minutes, using different routines that involved head and limb movements. As demonstrated in [18], when the Perception Neuron 2.0 MoCap system is operated in real time over extended periods, it is necessary to recalibrate it after each exercise routine to ensure proper functioning. This requirement is not apparent when teleoperation is performed with pre-stored movement routines in the Axis Neuron software. Furthermore, no significant latency was observed in the transmission of movements from the hardware (Perception Neuron MoCap system) or in the TCP/IP communication between computing systems. This is satisfactory, considering that overcoming communication delays to achieve instantaneous motion replication is a significant challenge in this field of research [6]. The manufacturer has documented that the overall latency of the suit is less than 20 ms, which includes: sensor calculation time (<13 ms), data transmission time from the hardware (<2 ms), and calculation time in the Axis Neuron software (<5 ms) [19]. However, to obtain experimental data, 100 recordings were taken from the Windows PerceptionNeuronROSserial application. The transmitted data showed an average rate of 38.20 fps, with a standard deviation of 0.47 among the recorded data. The system's latency is imperceptible to the operator.

Design constraints were influenced by the angular limitations of the robot. If the movement of the head, arms, and legs of the non-technical user exceeds the joint movement limits of the NAO robot, the robot will attempt to find a solution to approximate the movement. Regarding the location of the non-technical operator, experimentation showed that they can be positioned up to 10 meters away in either an open or closed space without significantly affecting the data transmission via Wi-Fi from the Perception Neuron 2.0 hardware to the Axis Neuron software. Due to the advantages of capturing movements with an inertial system, the non-technical operator can assume any pose and be effectively tracked by the system, even in the presence of objects [20]. This ensures that movement is not misinterpreted due to occlusion or darkness. Below are some results from two movement routines established to verify the NAO robot's imitation of the arm and leg joints. The movement routines set up for this study did not include activities involving fine motor skills, such as grasping an object, or gross motor skills that require stabilization of the robot's center of mass for single-leg or double-leg support without falling, such as walking.

In Figure 4, the non-technical operator starts with the shoulders flexed at 90º. They then perform shoulder adduction in the horizontal plane and shoulder abduction downward from that position. Next, the user performs shoulder abduction accompanied by elbow flexion to touch their head. Angle data are captured using the inertial MoCap

Figure 4. The NAO robot mimics an arm movement routine performed by the non-technical operator.



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system. From these results, it is observed that the NAO robot tracks the movement in an acceptable manner.

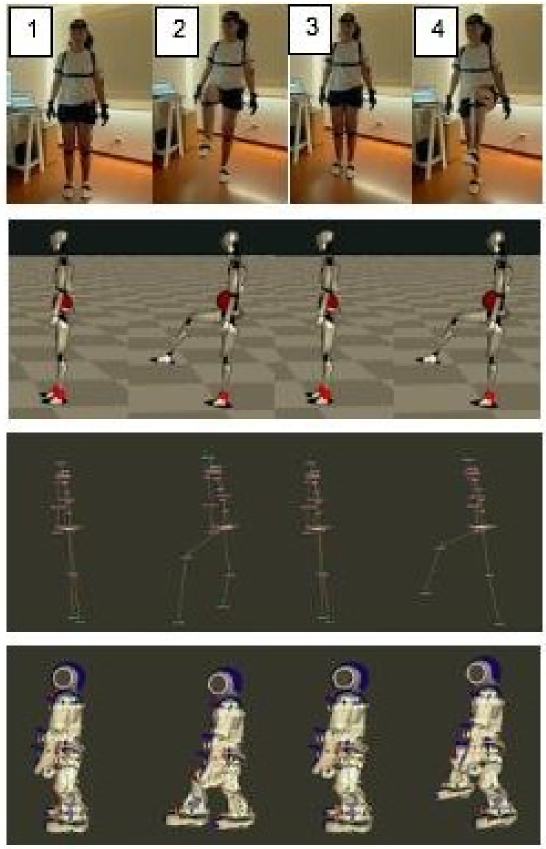
In Figure 5, the non-technical operator begins with a bipodal stance with knees extended, then performs a 90º flexion of the right knee accompanied by hip flexion. They return to the initial position and perform a 90º flexion of the left knee while on a single leg, and then return to the initial position with knees extended. Angle data from the movement are captured using the inertial MoCap system. From these results, it is observed that the NAO robot tracks the movement in an acceptable manner.

Below are some results from the evaluation of joint angles recorded by the NAO robot and the operator (using Perception Neuron) after executing the previously shown movement routines, aimed at validating the NAO robot's imitation of different joint segments with the proposed teleoperation system.

In the first experiment (Figure 4), a series of graphs (Figure 6) illustrate the NAO robot's imitation of shoulder adduction in the horizontal plane and shoulder abduction downward, represented by the Roll angle, as well as left elbow flexion assessed by the Yaw angle. This movement, accompanied by left shoulder flexion, is performed by the non-technical operator and recorded using the Perception Neuron MoCap system.

The result is an acceptable imitation of the

Figure 5. **The NAO robot mimics a leg movement routine performed by the non-technical operator.**



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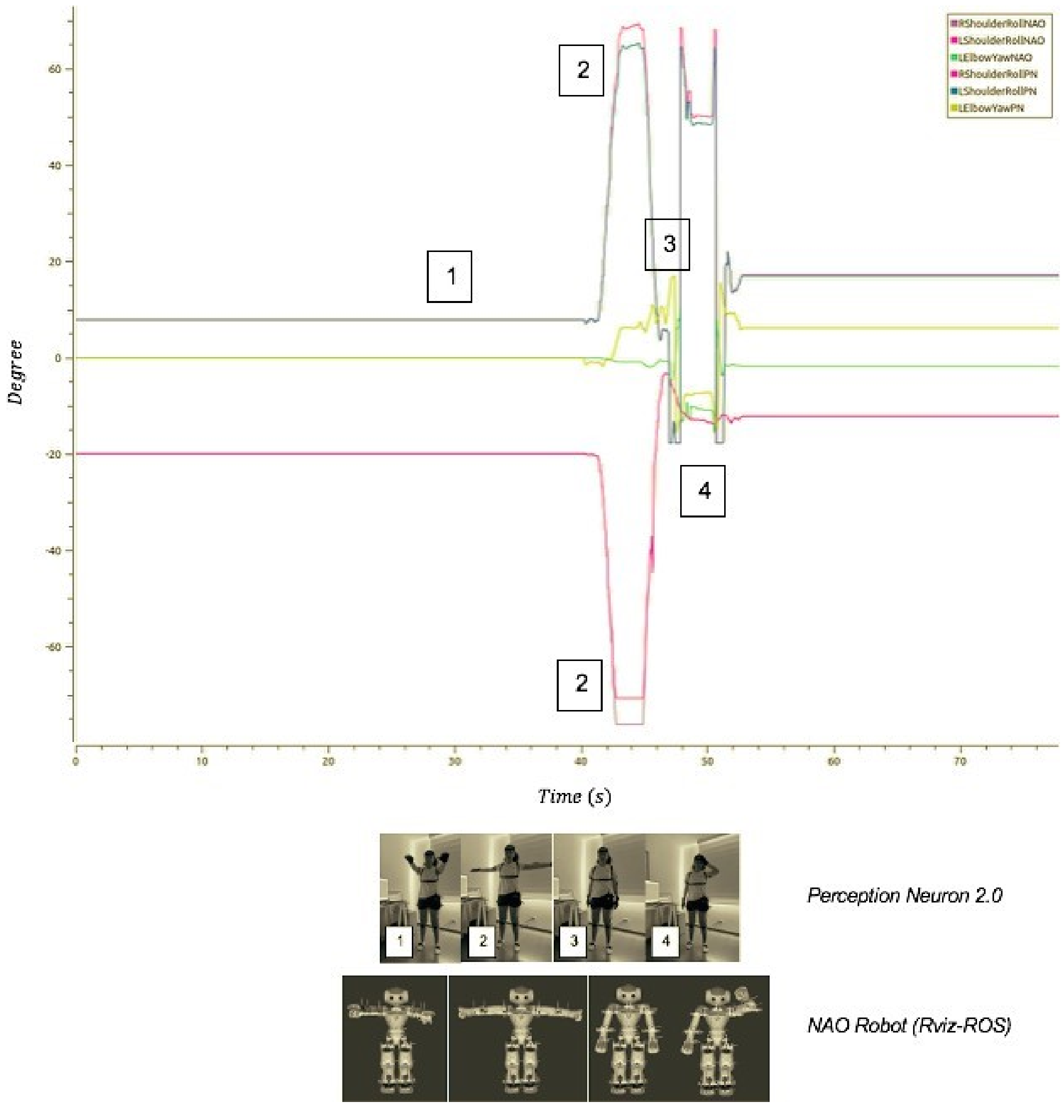
movement tracked by the NAO robot in its RShoulderRoll and LShoulderRoll joints; the LElbowYaw joint shows continuous tracking, with some variability in stability associated with the robot's attempts to find a solution for the arm positions it needs to imitate.

In the second experiment (Figure 5), a series of graphs (Figure 7) correspond to the NAO robot's imitation (viewed in Rviz-ROS) of 90º flexion of the right and left knees, movements accompanied by hip flexion to maintain a single-leg stance. This routine is performed by the non-technical operator using the Perception Neuron MoCap system. The imitation of the NAO robot in the RkneePitch and LkneePitch joints is evaluated. The imitation of the movement is very acceptable, although it is noted that the variation observed in the data during right knee flexion is due to data transmission disturbance from Axis Neuron during the experiment, resulting in a loss of the support foot. However, this does not imply that the NAO robot did not adequately imitate the information transmitted from the Perception Neuron.

In general, acceptable results were achieved for the teleoperation of the NAO social assistance robot (viewed in Rviz-ROS) using an inertial motion capture system. It is anticipated that this approach may be applied to future research studies in rehabilitation. Additionally, since movements can be recorded and saved in Axis Neuron, they can be replayed at any time.

Figure 6. Joint angles resulting from the movement routine established to assess arm motion in real time.



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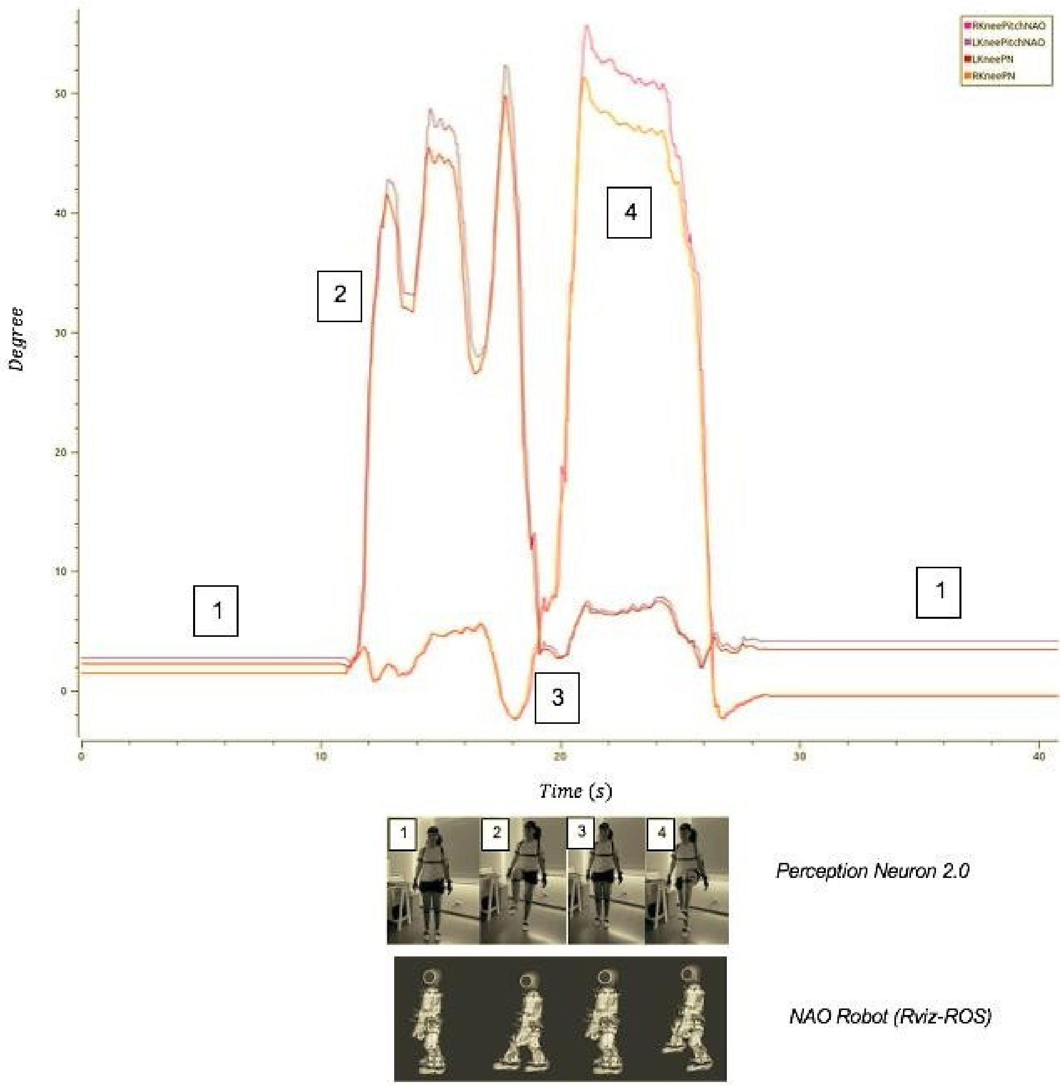
5. Conclusions

As evidenced in [11], the use of SAR robots has shown positive effects in children with movement, balance, and posture disorders. However, this study also highlights that research remains limited in determining the true potential of SARs. This potential should be harnessed by engineers and healthcare professionals to facilitate knowledge exchange and advance these solutions from engineering to clinical settings. As various studies reveal [21], traditional rehabilitation *lacks quantitative and systematic standards*, suggesting that new rehabilitation approaches should combine conventional methods with advanced equipment, such as motion capture systems. The results demonstrate the potential for practical clinical use.

This study successfully designed a method for capturing, recording, and transmitting movement

Figure 7. Joint angles resulting from the movement routine established to assess leg motion in real time.



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data to robotic rehabilitation platforms like the NAO social assistance robot in a virtual environment. In this context, the selected MoCap system meets the requirements of this research and its future application in rehabilitation. It allows for recording and evaluating therapeutic progress with quantitative standards, personalizing body dimensions, capturing movements without spatial limitations in indoor or outdoor environments under any lighting conditions, and exporting data in real-time to other programs. Additionally, data from the human skeletal model captured by the Perception Neuron 2.0 were received and transmitted to ROS, based on prior work by other researchers. This enables the design of a variety of applications with different focuses requiring the integration of IMU-based motion capture systems and robotic systems. Finally, real-time teleoperation experiments with pre-recorded movements were successfully conducted, with various routines and poses accurately imitated by the NAO robot viewed in Rviz-ROS. It should be noted that this system does not replicate the robot's movement in space, such as human gait, nor does it imitate movements requiring fine motor skills.

The system exhibits minimal latency even when the operator is 10 meters away from the computer capturing the information. Ultimately, the proposed solution allows the NAO robot (avatar) to execute a sequence of individualized and adaptive poses based on instructions given by a non-technical user, eliminating the need for specialized personnel to operate the robot.

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