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Design, development, and validation of interactive platforms for functional rehabilitation of people with motor disabilities

A Doctoral Thesis Presented for the Degree of Doctor at
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Fdo. Dr. Rafael Raya López

Fdo. Dr. Juan C. Moreno Sastoque

Fdo. Dr. Abraham Otero Quintana

“FOCUS. Follow One Course Until Success.”

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LIST OF ABBREVIATIONS

ABD	Abduction
ADD	Adduction
ADL	Activities of Daily Living
AMAT	Arm Motor Ability Test
AR	Augmented Reality
ARAT	Action Reach Arm Test
BBS	Berg Balance Scale
BBT	Box & Block Test
CAVE	Cave Automatic Virtual Environment
CEQ	Credibility and Expectancy Questionnaire
CIMT	Constraint-Induced Movement Therapy
COT	Common Object Test
CP	Cerebral Palsy
CPU	Central Processing Unit
CVA	Cerebrovascular Accident
DOF	Degrees of Freedom
FMA/FMT	Fugl-Meyer Assessment or Fugl-Meyer Test of Motor Recovery
FIM	Functional Independence Test
FRT	Functional Reach Test
GS	Gait Speed
HMD	Head-Mounted Display
ICD	International Classification of Diseases
IMI	Intrinsic Motivation Inventory
IMU	Inertial Measurement Unit
IPIQ-O	Interpersonal Interaction Questionnaire for Observers
LLD	Lower Limb Disorder
MAS	Modified Ashworth Scale
MBI	Modified Barthel Index
OLS-O/OLS-C	One-Leg Stand with Open eyes or with Close eyes
PA	Physical Activity
PCE	Physical Capacities Evaluation of Hand Skill

PQ	Presence Questionnaire
ROM	Range Of Motion
SCI	Spinal Cord Injury
SSQ	Simulator Sickness Questionnaire
SUS	System Usability Scale
TBI	Traumatic Brain Injury
TPT	Traditional Physical Training
TUG	Timed Up and Go
UEFT	Upper Extremity Function Test
ULD	Upper Limb Disorder
VE	Virtual Environment
VEQ	Virtual Embodiment Questionnaire
VR	Virtual Reality
VRT	Virtual Reality Training
WHO	World Health Organization
WMT	Wolf Motor Test
6-MWT	6-Minute Walking Test
9HPT	9 Hole Peg Test
9-MWT	9-Minute Walking Test
10-MWT	10-Meter Walk Test
30S-CST	30-Seconds Chair Stand Test

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RESUMEN

En esta investigación, las discapacidades motoras (DM) se definen como todas las anomalías motoras o de tonicidad de cualquier origen. Según la Novena Revisión de la Clasificación Internacional de Enfermedades de la OMS, (CIE-9) los diagnósticos de discapacidad motora pueden incluir la presencia de hemiplejia, tetraplejia, paraplejia, ataxia, atetosis y otros trastornos motores. Los tratamientos convencionales para las personas con DM comprenden una combinación de fisioterapia, ortopedia y terapia ocupacional. Aunque todavía existen discrepancias sobre las terapias de intervención más eficaces para esta dolencia, debido a la naturaleza compleja de este tipo de lesión, la mayoría de las metodologías de intervención física coinciden en la necesidad de realizar tareas de fuerza y repetición. Estas tareas permiten al paciente trabajar varias partes del cuerpo de forma estructurada y separada.

Sin embargo, en términos de motivación, las terapias tradicionales presentan dos inconvenientes principales: la monotonía del ejercicio y la falta de estímulos interesantes para el paciente que aumenten su motivación. Para mitigar este problema, se han desarrollado soluciones gamificadas que requieren de nuevos enfoques de diseño y creación de hardware o que implican la instalación de costosos equipos en la clínica o en el domicilio del paciente. No obstante, una solución plausible para aumentar la motivación del paciente es utilizar dispositivos comerciales de bajo coste y generar aplicaciones gamificadas específicas para esta demanda. En consecuencia, esta solución puede influir positivamente en su terapia de rehabilitación sin necesidad de crear costosos sistemas de hardware específicamente adaptados a las personas con discapacidades motoras.

La mayoría de las terapias basadas en videojuegos existentes se centran en dos propiedades fundamentales: inducir la mayor inmersión posible y dar feedback del rendimiento o de medidas de interés. La primera mejora el compromiso del usuario en una tarea eminentemente física, mientras que la segunda es necesaria para evaluar si los movimientos permiten al paciente alcanzar un objetivo funcional. Precisamente, con la intención de evaluar el movimiento durante la terapia, se pueden emplear sistemas de seguimiento de movimiento vestibles para videojuegos y *exergames* o dispositivos de realidad virtual (RV), ya que su capacidad para capturar con precisión los movimientos de las extremidades del usuario es perfectamente compatible con la realización de la actividad física con tecnología inmersiva. Varios estudios han puesto de manifiesto que las soluciones de rehabilitación basadas en entornos inmersivos son más eficaces que las tradicionales debido a tres cualidades esenciales. En primer lugar, mejoran el compromiso del paciente en la realización de la actividad. Los *exergames* aumentan el gasto energético del usuario e implican tareas tanto cognitivas como fisiológicamente gratificantes. Estas actividades altamente motivadoras probablemente promuevan la adherencia al juego. En segundo lugar, permiten la fidelidad física a un movimiento real: el paciente realiza movimientos similares a los que haría en una situación análoga durante su vida cotidiana. En último lugar, aportan fidelidad cognitiva a una situación real: el paciente debe realizar las actividades en un entorno diseñado para ser similar al mundo real.

El objetivo de esta tesis es diseñar, desarrollar y evaluar un sistema de realidad virtual para la rehabilitación integral de miembro superior e inferior de personas con discapacidades motoras. Para ello se generan dos plataformas que permitan la realización de actividades físicas de rehabilitación de miembro superior e inferior. Estos dos sistemas tendrán como fin la mejora de la movilidad y funcionalidad de las personas con patologías neurológicas o discapacidades motoras y adherencia al entrenamiento físico promovido por el sistema gamificado. El objetivo general que engloba ambos sistemas es la promoción de la adherencia y motivación del usuario al entrenamiento físico para agilizar o mantener el proceso de rehabilitación funcional de la extremidad correspondiente. Cada plataforma se ha desarrollado utilizando distintos dispositivos de RV de acuerdo con los requisitos de diseño de la actividad física a realizar, el modo de uso, el sistema de análisis de movimiento y la arquitectura del sistema.

Plataforma de realidad virtual para rehabilitación de miembro superior

En los proyectos marco POWERUP Retos 2018-097122-A-100 y el proyecto JIRAFA con referencia IDI-20191120, se desarrolla una aplicación de RV para aportar un sistema de tele-rehabilitación funcional de miembro superior de personas con enfermedades neurológicas o lesiones neuromotoras. Esta plataforma de RV llamada FarmDay busca ofrecer un conjunto de juegos que promuevan la realización de actividades de la vida diaria que estén expresamente diseñados para la ejecución de movimientos de acuerdo con rangos de movilidad funcional para cada articulación implicada. El diseño de cada juego de la plataforma virtual ha implicado la definición concreta de los rangos de movimientos que se deben alcanzar en cada acción por articulación: cervical, hombro, codo y muñeca. La estrategia de gamificación de las actividades se basa en el alcance de objetivos. Así, cada actividad se compone de una secuencia de acciones bimanuales que el usuario debe realizar con el propósito de completar la tarea. El alcance de estos objetivos conlleva la realización de movimientos de los distintos segmentos corporales implicados en los movimientos habituales de actividades de la vida diaria. La aplicación contiene un total de 6 juegos, 3 de ellos inspirados en actividades habituales de la vida diaria y otros 3 inspirados en actividades de la vida en la granja. Cada uno de estos 6 juegos está diseñado para trabajar distintos objetivos funcionales. Cabe destacar que el modo de interacción de esta experiencia de RV se basa en el agarre de los mandos o controladores del dispositivo de RV. Por ello, el diseño de los juegos y la secuencia en las acciones está adaptado a la manipulación de los controladores. Por este motivo, cada actividad ha sido evaluada por fisioterapeutas expertos para constatar que permite la realización precisa de los movimientos preestablecidos respetando la fidelidad física del movimiento.

La principal contribución científico-técnica de este desarrollo consiste en generar una guía de diseño para la construcción de entornos virtuales para la rehabilitación bimanual funcional. Esta guía representa una pauta no encontrada hasta la fecha en la literatura. Así pues, con el objetivo de generar dicha guía para el diseño de actividades funcionales para rehabilitación de miembro superior en realidad virtual, se ha validado el diseño y la viabilidad de uso de esta herramienta por cinco fisioterapeutas expertos en neurorrehabilitación de la Fundación de Lesionado Medular (FLM) y fisioterapeutas expertos en rehabilitación funcional de la Universidad CEU San Pablo.

Plataforma de realidad virtual para rehabilitación de miembro inferior

En el proyecto marco “Desarrollo y estudio de una plataforma interactiva y un sistema electrónico de pedaleo para rehabilitación funcional de personas mayores” con de la convocatoria de ayudas destinadas a la realización de doctorados industriales de la Comunidad de Madrid con referencia IND2019/TIC-17090 se desarrolla la plataforma denominada PedaleoVR. Esta plataforma de RV creada para la rehabilitación funcional de miembro inferior busca promover la actividad de pedaleo. Desde el punto de vista científico es conocido que la práctica de ejercicio de pedaleo con retroalimentación visual puede mejorar el control neuromuscular, el fortalecimiento de la extremidad inferior, la recuperación funcional de la marcha y el rendimiento general. Desde el punto de vista técnico, se busca definir una metodología que permita controlar el entorno virtual adaptando el estímulo visual a la cadencia de pedaleo estimada a partir del análisis biomecánico del movimiento de pedaleo. Para la estimación de dicha cadencia de pedaleo en tiempo real, se han integrado sistemas de captura de movimiento que transmiten en tiempo real los datos de aceleración y rotación angular de los segmentos al dispositivo de RV. Esta comunicación continua de datos cinemáticos permite realizar el análisis de la cadencia en el dispositivo de RV a la par que se renderiza el entorno digital. Como resultado, el sistema propuesto puede generar entradas sensibles para influir en la cadencia de pedaleo del usuario con el fin de mejorar el rendimiento en la actividad y fomentar los beneficios del ejercicio funcional. La principal contribución científico-técnica de este desarrollo consiste en la validación funcional y aceptación tecnológica de un sistema que integra un dispositivo de RV comercial de altas prestaciones con un dispositivo vestible. Este sistema permite la estimación de la cadencia de pedaleo basándose únicamente en el ROM de la cadera y que es independiente del equipo de pedales.

Con el desarrollo de PedaleoVR se lleva a cabo su caracterización técnica y evaluación funcional. En primer lugar, desde la perspectiva técnica, se estudia la fiabilidad y robustez del sistema comparado frente al sistema de referencia en la práctica clínica, MOTOmed™. También se estudia su precisión en la estimación de cadencia a distintas velocidades: baja (30rpm), moderada (60rpm) y alta (90rpm). Como resultado de esta caracterización se concluye que la aplicación de esta plataforma de RV debe limitarse a ejercicios de velocidad baja y moderada, no recomendando su uso en velocidad altas debido a la reducción en la precisión de la estimación de la cadencia por el sistema. La extensión de estas conclusiones en la práctica de actividad física implicaría que la plataforma es adecuada como una herramienta atractiva para la práctica de pedaleo en rehabilitación, ya que en este contexto se asume una velocidad de pedaleo baja-moderada.

En segundo lugar, se persigue evaluar la aceptación, satisfacción, credibilidad, motivación intrínseca, usabilidad y seguridad con el fin de evaluar las características de diseño de PedaleoVR. La validación de estos aspectos se ha llevado a cabo en dos poblaciones distintas. La primera son 20 pacientes neurológicos de la clínica Centro Lescer (Comunidad de Madrid, España), que presentan ataxia o hemiparesia, y por lo tanto ven afectado su control y coordinación motora de miembro inferior. En el marco del proyecto SWALKER y fruto de la colaboración con el Grupo Albertia Servicios Sociosanitarios (Comunidad de Madrid, España), se reclutan 18 participantes adultos mayores de 65 del que presentan un deterioro motor en miembro inferior debido al propio proceso de envejecimiento o a causa de haber sufrido una fractura de cadera.

Sistemas de captura de movimiento vestibles

La cuantificación de los parámetros cinemáticos, como las orientaciones de los segmentos corporales y los rangos de movimiento articulares son esenciales en la monitorización precisa de la actividad física. Esta cuantificación del movimiento humano proporciona parámetros biomecánicos relevantes asociados a la valoración del ejercicio o del estado funcional de la persona, e incluso permite evaluar la presencia de un trastorno motor. Recientemente, se ha observado un incremento en el uso de los dispositivos electrónicos vestibles en el ámbito de la medicina deportiva y la rehabilitación, debido a la libertad de movimiento que ofrecen estos sistemas y la gran cantidad de datos que capturan con elevada precisión. Muchos de los dispositivos electrónicos vestibles diseñados para la captura de movimiento en tiempo real consisten en unidades de medición inercial (*inertial measurement unit*, IMU), las cuales contienen sensores triaxiales: giróscopo, acelerómetro y magnetómetro. Las IMUs son elementos lo suficientemente pequeños para que resulten dispositivos vestibles cómodos que proporcionan un seguimiento sistemático, objetivo y fiable del movimiento sin obstáculos.

La principal consideración en el empleo de IMUs para la evaluación cinemática de las articulaciones es la alineación correcta de los ejes de los sensores con los ejes de los segmentos anatómicos. Este problema se resuelve habitualmente mediante procedimientos de calibración para el cálculo de la orientación relativa entre los marcos de la IMU y los marcos del segmento corporal, asumiendo esta relación de marcos invariable en el tiempo. Consecuentemente, el uso de sensores inerciales como sistemas de captura de movimiento precisos de articulaciones del miembro superior e inferior, requiriendo de la definición de un convenio específico para la articulación en cuestión que permita el cálculo de la orientación de estas en los planos anatómicos de movimiento: sagital, frontal y transversal.

Organización del documento

En el primer capítulo se ha realizado una revisión del estado del arte en la utilización de nuevas metodologías de rehabilitación funcional en personas con deterioro motor y neuromotor en miembros superior e inferior. Se incluye una introducción del uso de sensores inerciales como marcadores en RV. El segundo capítulo presenta las hipótesis y objetivos del presente trabajo. Además, detalla el contenido de los capítulos posteriores, que incluyen los tres artículos científicos de esta tesis por compendio y un cuarto artículo científico que se encuentra en revisión. El tercer capítulo presenta el estudio del primer prototipo de integración del sensor inercial con el dispositivo de RV. Este estudio presenta la valoración de rango articular de codo en plano sagital realizada por el prototipo y la comparación de la precisión de medida de este sensor frente al controlador propio del dispositivo de RV. El cuarto capítulo recoge el diseño, desarrollo y evaluación por expertos de la herramienta FarmDay para rehabilitación funcional de miembro superior basada en actividades de la vida diaria. El quinto capítulo introduce el diseño y desarrollo de la plataforma PedaleoVR, la cuál presenta una segunda propuesta de integración del sensor inercial con el dispositivo de RV respecto al prototipo presentado en el capítulo segundo. Además, se incluye el estudio de caracterización técnica de la plataforma comparada con el *gold-standard*, MOTOmed™, en sistemas de pedaleo. El capítulo sexto expone dos estudios de evaluación funcional de PedaleoVR realizados por dos poblaciones que presentan deterioro motor en miembro inferior. El primer estudio consiste en la evaluación de la credibilidad, la expectativa, la motivación intrínseca y la usabilidad de la herramienta por pacientes con ataxia o hemiparesia. El segundo estudio consiste en la evaluación de la seguridad y los efectos adversos provocados por la simulación, la satisfacción, la sensación de presencia y la usabilidad de la plataforma por población geriátrica. Estos estudios con humanos cuentan con la aprobación del Comité de Ética de la Investigación de la Universidad San Pablo-CEU, y el protocolo clínico aplicado está registrado en ClinicalTrials con la referencia NCT05162040. Estos estudios se incluyen en este proyecto de tesis por completitud del trabajo realizado, aunque actualmente estén bajo revisión. El resumen general y la discusión del trabajo realizado, así como las observaciones finales y sugerencias de trabajo futuro se recogen en el último capítulo de este documento.

ABSTRACT

Motor disabilities are defined as all motor or tonicity abnormalities of any origin. Conventional treatments for people with motor disabilities comprise a combination of physical therapy, orthopaedics, and occupational therapy. Although there still are discrepancies about the most effective interventional therapies for this condition, due to the complex nature of this type of injury, most physical intervention methodologies agree on the need for strength and repetition tasks. These tasks allow the patient to work various parts of the body in a structured and separate manner.

However, in terms of motivation, traditional therapies have two main drawbacks: the monotony of the exercise and the lack of interesting stimuli for the patient to increase motivation. To address this problem, there are gamified solutions that require new approaches to its design and require the creation of custom hardware, or that involve the installation of expensive equipment in the clinic or in the patient's home. However, a plausible solution to increase patient motivation and, consequently, positively influence their rehabilitation therapy without the need to create expensive hardware systems specifically adapted to people with motor disabilities is to use low-cost commercial devices and generate gamified applications specifically for this demand.

Most existing video game-based therapies focus on two fundamental properties: inducing as much immersion as possible and accurately tracking the patient's movements. The former enhances the user's engagement in an eminently physical task, while the latter is necessary to assess whether the movements have been performed correctly. Precisely for the purpose of assessing movement during therapy, wearable motion tracking systems can be used for video games (exergames) or virtual reality (VR) devices, as their ability to accurately capture the movements of the user's limbs is perfectly compatible with the performance of physical activity with immersive technology. Several studies have shown that rehabilitation solutions based on immersive environments are more effective than traditional ones due to three essential qualities. First, they improve patient engagement in the performance of the activity. Exergames increase the user's energy expenditure and involve both cognitively and physiologically rewarding tasks. These highly motivating activities are likely to promote adherence to the game. Second, they allow physical fidelity to a real movement: the patient performs movements similar to those he would make in an analogous situation during everyday life. Finally, they provide cognitive fidelity to a real situation: the patient must perform the activities in an environment designed to be similar to the real world.

The objective of this thesis is the creation of two platforms that enable the performance of upper and lower limb physical rehabilitation activities, respectively. These two platforms will aim to improve the mobility and functionality of people with neurological pathologies or motor disabilities as a benefit of the adherence to physical training promoted by the gamified system.

The general objective that encompasses both platforms is the promotion of the user's adherence and motivation to physical training to speed up or maintain the functional rehabilitation process of the corresponding limb. Each tool has been developed using different VR devices according to the design requirements of the physical activity to be performed, the mode of use, the motion analysis system, and the system architecture.

For both functional rehabilitation platforms, the integration of inertial sensors has been considered to enable accurate motion capture. Initially, the accuracy of a prototype integration of the ENLAZA commercial sensor on the commercial VR device Oculus Quest 2 was studied and technically analysed. In the case of the lower limb platform, called PedaleoVR, the integration system was refined. This platform was analysed from the point of view of technical functionality and usability by two target populations: elderly people with motor impairment and patients with neurological pathologies presenting ataxia or hemiparesis. In the case of the upper limb platform, it was decided to dispense with the use of inertial sensors and use the controllers to estimate the user's functional movements. The VR platform, named FarmDay, was designed to offer different gamified activities of daily living (ADL) to promote bimanual coordination. The design and usability of this platform has been validated by experts

The first chapter reviews the state of the art in the use of new functional rehabilitation methodologies in people with motor and neuromotor impairment in upper and lower limbs. The second chapter contains the objectives and hypotheses of the thesis work. Chapters three, four and five contain the already published scientific articles that make up this thesis by compendium of publications. In particular, the third chapter presents the first approach for communicating the inertial sensor with the VR device for the assessment of elbow joint range in sagittal plane and the comparison of the measurement accuracy of this sensor versus the VR device's own controller. The fourth chapter covers the design, development, and expert evaluation of the FarmDay tool for upper limb functional rehabilitation based on ADL. The fifth chapter introduces the design and development of PedaleoVR, which presents a technical improvement in the integration of the inertial sensor with the Oculus Quest. In addition, it includes a study of the technical characterization of the platform compared to the gold-standard in pedalling systems. The sixth chapter presents two studies of functional evaluation of PedaleoVR performed by two populations with motor impairment in the lower limb. The first study consists of the evaluation of the credibility, expectancy, intrinsic motivation, and usability of PedaleoVR by patients with ataxia or hemiparesis. The second study consists of the evaluation of safety and adverse effects caused by the simulation, satisfaction, sense of presence and usability of the platform by a geriatric population. The general summary and discussion of the work performed, as well as the final observations and suggestions for future work are included in the last chapter of this document.

CHAPTER 1: INTRODUCTION

1.1. Introduction to motor disabilities

Current treatments for motor deficits are not always effective in alleviating the consequences that infiltrate the daily living. In fact, diseases that are self-limiting or morbidity experiences resulting from trauma, stroke, neurological illnesses, or arthritis are especially noteworthy as causes of disability in some countries (World Health Organization, 1980). In 1980, the World Health Organization (WHO) stressed the need to review the framework, known as the International Classification of Diseases (ICD) to collect all these experiences, which are particularly latent in the case of chronic and progressive or irreversible disorders. This effort established a conceptual schema that includes four concepts that were characterized as occurring sequentially: disease, impairment, disability, and handicap. Previously, in gerontology and geriatric medicine, Saad Nagi developed one of the most influential models of disabilities where sequence follows: active pathology, impairment, functional limitations, and disability (Nagi, 1965). In both pipelines, disability was defined as ‘a reflection of the consequences of an impairment in terms of functional performance and activity by the individual; disabilities thus represent disturbances at the level of the person’ (World Health Organization, 1980). And therefore, the umbrella term of “disability” is the cornerstone for all those experiences consequence of neurodegenerative diseases, neurological lesions, or conditions of progressive musculoskeletal deterioration.

In this research, motor disabilities are defined as all motor or tonicity abnormalities of any origin. According to the Ninth Revision of the WHO International Classification of Diseases, (ICD-9) motor disability diagnoses may include the presence of hemiplegia, tetraplegia, paraplegia, ataxia, athetosis and other motor disorders. Motor disability occurs when a person exhibits a physical coordination significantly below what is expected for his or her age (Ribera & DeSouza, 2014). In that sense, experiencing a physical condition that permanently and irreversibly prevents a person from performing or learning motor tasks (Pinheiro, et al., 2011) and entails limitations in fine motor control, balance, agility, endurance strength and range of motion (Chang, Chen, & Huang, 2011) (Bullock & Mahon, 1995). Motor disabilities are therefore the product of dysfunction in gross, fine, ambidextrous or locomotion motor skills that lead to short-term deterioration of motor skills and in the long term may hinder muscle control.

We find different symptomatology whether the motor dysfunction’s origin is neurological or musculoskeletal. Disturbances in the voluntary motor control in the form of paresis, hemiparesis or paralysis are usually the consequence of a dysfunction in the pyramidal tract, being stroke disease one of the causes (Arboix & Martí-Vilalta, 2012). While loss of sensory or afferent pathways and coordination disorders are related to cerebellar lesions or alterations of the cortical motor programming, causing ataxia or apraxia (De Recondo, 1995).

Then, regarding the topography of the lesion, the motor weakness may occur as a disorder of one of the three forms of movement: voluntary, automatic, and reflex (Arboix & Martí-Vilalta, 2012). On the other hand, musculoskeletal disorders are diseases or injuries of the muscles, nerves, tendons, joints, cartilage, or spinal discs (Viceconti, et al., 2020), often being rheumatic diseases and muscle strains the cause of chronic pain with severe impact on the quality of life in adult population (March, et al., 2014) (Blyth, Briggs, Schneider, Hoy, & March, 2019). Here, it is listed some of the most important conditions that lead to motor impairments, and their current prevalence is shown in Figure 1.

Cerebral palsy

Cerebral palsy (CP) is defined as a group of permanent disorders of the development of movement and posture, causing activity limitation (Hallman-Cooper & Rocha Cabrero, 2021). This disease is the most common disability of childhood that affects motor function. It causes brain damage, either by brain injury or by abnormal development of the brain (Paul, Nahar, Bhagawati, & Kunwar, 2022) (Hallman-Cooper & Rocha Cabrero, 2021). CP symptoms are heterogeneous but they generally include abnormal contraction of muscles, a hindering of the reflexes, postural changes and balance, and movement activity limitation or degradation that is often accompanied by sensory disturbances (Ribera & DeSouza, 2014) (Paul, Nahar, Bhagawati, & Kunwar, 2022).

Spinal cord injury

Spinal Cord Injury (SCI) is any lesion to the spinal cord resulting in a change, either temporary or permanent, in the cord’s normal motor, sensory, or autonomic function (Dawodu, 2018). The most common causes of SCI are traumatisms of the spine, fracture or dislocation of a vertebrae and damages of the spinal cord tissue (Ribera & DeSouza, 2014). SCI can be classified as complete or incomplete depending on the level and the extent of the injury and the loss of motor and sensory function (ASIA) (American Spinal Cord Injury Association, 1982). SCI affects the conduction of sensory or motor signals across the injured location.

Muscular dystrophy

Muscular dystrophy is an umbrella term that includes several muscular diseases as Spinal Muscular Atrophy, Amyotrophic Lateral Sclerosis, and also Duchenne Muscular Dystrophy or Congenital Muscular Dystrophy, which is the second most common single gene muscular dystrophy disorder in Western countries (Emery, Muntoni, & Quinlivan, 2015). Typified symptoms of these diseases are muscle weakness affecting first to the proximal lower limb and trunck and later to the upper limb and distal muscles. The disruption of the signals from the nerves causes involuntary muscle contractions and muscle controlling, persistent twitches and even cardiopathies or arrhytmias (Yiu & Kornberg, 2015). Muscular dystrophy diseases are degenerative which may cause the inability to walk or to control facial muscles in the long term.

Cerebrovascular Accident

Cerebrovascular accident (CVA) or stroke is a syndrome of rapid onset of focal cerebral deficit with no apparent cause other than a vascular one (Hatano, 1976). About 80% to 90% of patients with stroke have motor impairments after the accident (Arboix & Martí-Vilalta, 2012). Motor neglect, apraxia, visuomotor ataxia or gait ataxia are severe deficit outcome forms of stroke. But the most common motor-deficit profile that affects at least two-thirds of patients is hemiparesis with uniform motor weakness of the limbs (Caplan, 1993).

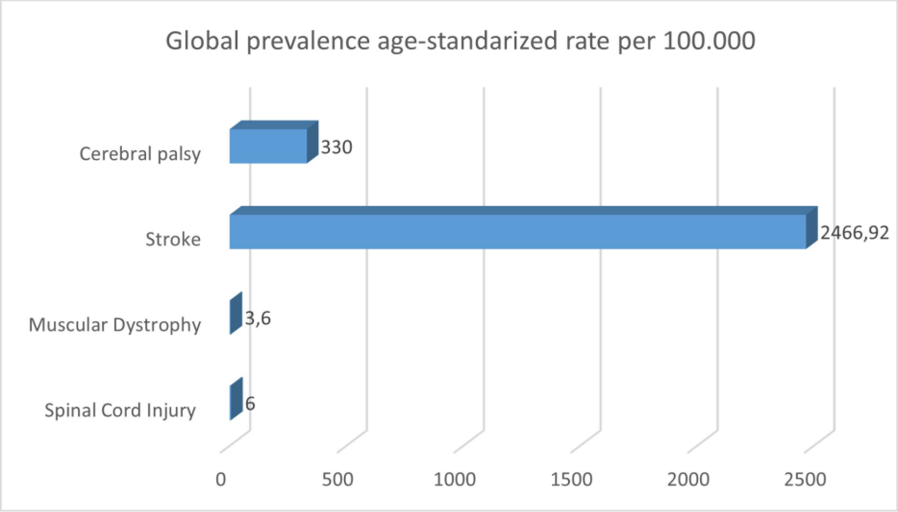

Figure 1. Global prevalence of cerebral palsy, stroke, muscular dystrophy and spinal cord injury. Data sources: (WHO, 2022) (Gibson, 2022) (Steeves, Day, Dykeman, Jette, & Pringsheim, 2012).

Aging-related motor dysfunction

Physiological aging affects motor control as it can be observed a gradual decrease of motor abilities related with the significant breakdown of specific neural systems with aging. This progressive deterioration draws symptoms like tremor, rigidity, loss of balance and gait disorders. The dysfunction of the central and peripheral nervous systems and neuromuscular system causes coordination of bimanual and multi-joint movements difficulties as well as difficulties with balance and gait (Tang & Woollacott, 1998). According to several researches, the age-related degradation of the cerebellum and the propioceptive system may be the origin of the deficits in multi-joint coordination and the inestability in temporal bimanual coordination (Raz, et al., 2005) (Goble, Coxon, Wenderoth, Van Impe, & Swinnen, 2009). Moreover, the decline in motor performance is also observed as an increase of variability and slowing of movement (Contreras-Vidal, Teulings, & Stelmach, 1998) (Darling, Cooke, &

Brown, 1989).

1.1.1. Motor system impairments

People who suffer the aforementioned conditions manifest similar motor dysfunctions due to a chronic or progressive impairment. Here we summarize the most encountered motor system impairments in patients with motor disabilities and elderly people.

Muscle tone

Understanding the muscle stiffness in physical terms as the resistance to movement, muscle tone is defined as the specific elastic and/or viscoelastic stiffness in the absence of motor unit activity or contracture (Simons & Mense, 1998) (Svend Clemmensen, 1951). Hypertonicity generally occurs because of loss of supraspinal inhibition to the spinal cord (Lance, 1980) (Porter & Lemon, 1993). Hypertonia includes different conditions such as spasticity, which is a velocity-dependent increase in tonic stretch muscle tone (Lance, 1980), rigidity (Sanger, et al., 2003) or dystonia (Poewe, 1989). While hypotonicity occurs as a result of decreased or absent neural drive to the muscles in patients with cerebellar lesions and peripheral nerve damage it also occurs in elderly people with degenerative neuromuscular diseases.

Paresis

The disturbance of voluntary movement in the form of paresis or paralysis are the most common motor impairment consequence of CVA or damage to the corticospinal system (Arboix & Martí-Vilalta, 2012). Paresis is the reduced ability to voluntarily activate the spinal motor neurons (Sathian, et al., 2011) or the quantitative lack of command directed to agonist muscles to generate force or movement. Relative immobilization of paretic body parts leaves some of the muscles and their surrounding soft tissues immobilized in a shortened position (Yelnik, Simon, Parratte, & Gracies, 2010).

Ataxia

Ataxia describes a lack of coordination, meaning a group of neurological disorders in which motor behaviour appears uncoordinated (Johns Hopkins Medicine, 2022). The three main categories of ataxia are: vestibular ataxia, general proprioceptive ataxia, and the cerebellar ataxia. Hence, ataxia may have both motor and sensory components, the first and most common symptom for patients with ataxia is gait imbalance (Luo, Wang, & Lo, 2017).

Akinesia, hypokinesia or badykinesia

These terms cover a broader range of motor function disturbances (Berardelli, Rothwell, Tohompson, & Hallett, 2001) (Bloem, Hausdorff, Visser, & Giladi, 2004). They are often linked to Parkinson’s disease (Schilder, Overmans, Marinus, van Hilten, & Koehler, 2017), but also linked to elderly people with dementia or degenerative aging processes. Typically, people with bradykinesia or hypokinesia struggle with the onset of movement and can freeze during its performance (Morris M. , Iansek, McGinley, Matyas, & Huxham, 2005). Severe bradykinesia often includes muscle weakness, rigidity, tremor, movement variability and slowing of thought (Berardelli, Rothwell, Tohompson, & Hallett, 2001).

Dystonia

Dystonia is a movement disorder that causes involuntary muscle contractions, abnormal postures of the arms and legs or trunk, neck and face (Stanley, 1987) (Ribera & DeSouza, 2014) (Casellato, et al., 2012) wich are sometimes task-specific. The sustained contractions lead to repetitive slow or rapid twisting movements that may often be confused with spasticity or rigidity related to cerebral palsy (Tarsy & Simon, 2006).

1.1.2. Rehabilitation for motor disabilities

Physical rehabilitation is essential to the recovery of normal daily living functions (Ribera & DeSouza, 2014). This notion contrasts with interventions studied in the past for motor impairment following brain injury or stroke which tended to be pharmacological rather than focus on physical training (Marshall, et al., 2007). Added to this, outcome measures in the rehabilitation process were mostly focused on impairment rather than on functional outcomes. Currently, intervention strategies seek to provide by all possible means a recovery of lost functions and to increase autonomy in the person's activities of daily living, considering the remaining disabilities. Thus, complex (and diverse) rehabilitation interventions represent the mainstay of aftercare following the detection of motor impairment.

Task-specific training

For this thesis, efforts have been made to review exercise interventions aimed at motor system impairments. One approach of rehabilitation strategy is to treat motor disabilities with exercises directed at specific motor deficits with the aim of improving the overall functional ability, despite the origin of the motor dysfunction. Marshal *et al.* (Marshall, et al., 2007) study gathers concrete ideas on different rehabilitation practices based on scientific evidence from previous studies. Regarding directed therapy at specific deficits they find moderate evidence of the functional improvement in ability that specific sit-to-stand exercise brings. On the other hand, they point to limited evidence that embedded reaching exercises are more effective than conventional reaching exercises. Similarly, they pointed to early evidence that specific balance and coordination exercises are more effective than traditional generic muscle training exercises.

High-dose repetitive task-specific training improves practiced trajectories and allows generalization only of movements performed within the practiced regions (Huang & Krakauer, 2009) and is therefore unlikely to result in movement generalization (Pacheco, Lafe, & Newell, 2019). However, if the specific tasks trained allow gaining specific functionality, such as gait function training, then they present an acceptable solution.

Muscle strenghtening

In general, motor weakness is treated with strengthening exercises and task-specific intensive therapy, while abnormalities of muscle tone are treated with stretching, task-specific practice and serial casting (Lipson Aisen, et al., 2011). Of the practices mentioned, regarding muscle strengthening it can be differentiated between isokinetic muscle strengthening and conventional muscle strengthening exercises. Isokinetic mucle strengthening uses computer-driven isokinetic dynamometers to train muscle force (Hammami, et al., 2012). Conventional muscle strenthening techniques consist of progressive active exersices against resistance for the paretic extremity. Those exercises can be either preformed against manual resistance exerted by the clinician or using weight-bearing equipment. Simultaneous strength and endurance training is the most effective strategy to improve neuromuscular and cardiorespiratory functions in the elderly population (Cadore, Pinto, Bottaro, & Izquierdo, 2014). According to recent evidence, concurrent training performed at a moderate weekly frequency and at a moderate intensity and volume (Hagedorn & Holm, 2010) (Ehsani, et al., 2003) can promote remarkable gains in muscle hypertrophy, endurance gains, increase of aerobic capacity and general fitness (Cadore, Pinto, Bottaro, & Izquierdo, 2014). Concurrent strength and endurance training in elderly include treadmill walking (Villareal, Smith, Sinacore, Shah, & Mittendorfer, 2011) (Hagedorn & Holm, 2010) step-ups, stair climbing, and stationary cycling.

Bilateral training therapy and rhythmic cueing strategy

When the motor impairment is not symmetrical or homogeneous in all limbs, having some type of paresis, bilateral training strategies are usually applied. This technique is based on the literature on motor control and states that the movement of the non-paretic limb supports the movement of the paretic limb when a movement is performed simultaneously (Mudie & Matyas, 2000). Therefore, bilateral training consists of performing repetitive symmetrical or asymmetrical movements, as the basic human tendency towards in-phase (symmetrical movements) or anti-phase (alternating movements) coordination with the same frequency is well known (Swinnen, Dounskaia, & Duysens, 2002) (Ridderikhoff, Peper, & Beek, 2005). For the upper extremity, this strategy is generally applied in bilateral rhythmic coordination activities, while for the lower extremity, anti-phase coordination activities such as walking or pedalling exercises are executed, because these activities promote the repetition of the same movement pattern alternatively. Additionally, these exercises would not only favor the recovery of the paretic leg, but might also have an impact on the recovery of gait function. Actually, an extention of this methodology are the therapies based on rhythmical sensory cueing (Morris, Iansek, & Galna, 2008). Its principle is to provide auditory, visual or haptic/sensory rhythmical cueing to guide the gait speed or the cycling cadence.

Motor learning, motor observation, motor imitation and motor imagery

At present, there are other useful motor learning techniques, such as bimanual coordination training based on motor observation and moto-imitation or therapies based on motor imagery. Motor learning is the process of relearning a previously acquired movement pattern that has been lost due to the absence of neuronal circuits associated with the ability to execute or learn movements (Small, Buccino, & Solodkin, 2012). The traditional approach to relearning is to implement task-specific repetitive movement practice (as depicted in Figure 2). However, repetition of these movements is likely to lead to small improvements in motor performance or even to the acquisition of an impaired movement pattern (Levin & Demers, 2021) (Takeuchi & Izumi, 2012). This rehabilitation approach requires the patient to imitate visually perceived actions, as there is evidence that the observation of an action and its motor representation occur through the same brain circuits (Small, Buccino, & Solodkin, 2012). Therefore, enhancing the visualization of a motor task and trying to represent it may promote the learning of the task (Hatem, et al., 2016).

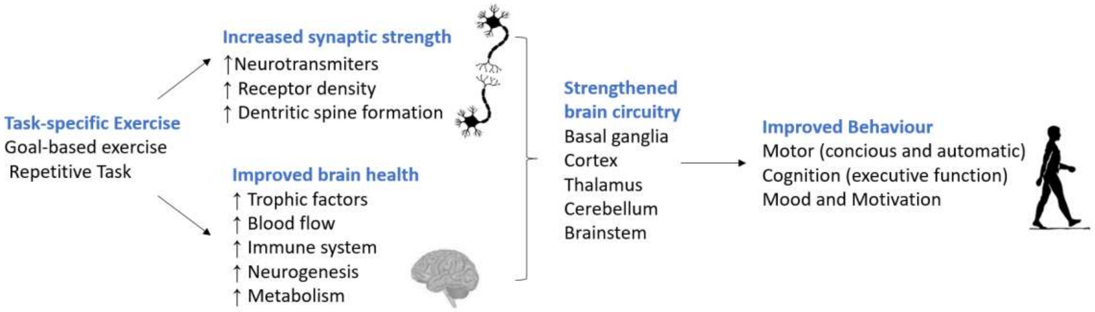

Figure 2. Effects of task-specific therapy in facilitating improved motor function, motor cognition and mood (Petzinger, et al., 2013).

Progressive motivational training and feedback.

It has been studied by many authors that the induction of new motor learning should be approached as a progressive practice whose challenge is adapted to the capability of the person (Kleim & Jones, 2008) (Winstein & Kay, 2015). In this way, learning can be modulated through progression in the level of difficulty. Precisely, the challenge point theory of motor learning (Guadagnoli & Lee,

2004) indicates that learning is enhanced if the individual is appropriately challenged by adjusting the difficulty level of the task. The manipulation of the difficulty level is also related to the level of motivation, which is a key factor in motor learning (Nudo & Milliken, 1996). Reward-based motivation has been shown to improve long-term skill (Abe, Schambra, & Wassermann, 2011). Even autonomy, self-confidence, support and social relatedness are motivational aspects that promote motor learning (Ostir, Berger, & Ottenbacher, 2008) (Krakauer & Shadmehr, Consolidation of motor memory, 2006). Moreover, the feedback provided should be task-depent sensible and should change with the evolution of the learning skill process (van Dijk, van der Sluis, & Bogers, 2017). Feedback can inform the individual about his performance and allow him to modify his actions dynamically (Hatem, et al., 2016).

Training induced functional changes

A wealth of literature exists highlighting the importance of propioceptive feedback in the control of voluntary movements (Goble, Coxon, Wenderoth, Van Impe, & Swinnen, 2009). In fact, several studies demonstrated that, when feedback is unavailable, people with motor disabilities may have difficulties calibrating hands position in space (Teasdale, et al., 1993), mantaining constant muscle force or movement amplitudes (Rothwell, Traub, Day, Obeso, & Thomas, 1982), controlling timing of muscle contractions to control limb dynamics (Sainburg, Ghilardi, Poizner, & Ghez, 1995), and producing coordinated gait patterns (Lajoie, et al., 1996). Recent studies have focused on evaluating the efficacy of physical activity interventions for the preservation or improvement of proprioceptive function in the elderly. In light of the evidence that proprioceptive acuity can be restored with physical training-based interventions provides a plausible intervention strategy for the elderly. Activities that have demonstrated a benefit for sensorimotor reorganization are those activities that involve moderate speed movements and continuous control of body and joint position, such as tai-chi (Tsang & Hui-Chan, 2003) and swinging, such as golf (Tsang & Hui-Chan, 2004)

It should be noted that certain sports/activities that engage more gross motor tasks may not be dependent on proprioceptive feedback, although they are effective in improving overall fitness (Goble, Coxon, Wenderoth, Van Impe, & Swinnen, 2009). For example, cycling activity is recommended for neuromuscular and cardiovascular improvement with gains in muscle strengthening and endurance (Peng, Chen, Lai, & Chen, 2011) and also promotes bilateral motor coordination (Ambrosini, Ferrante, Ferrigno, Molteni, & Pedrocchi, 2012).

Key points of rehabilitation strategies for motor disabilities

- Performing repetitive symmetrical or asymmetrical movements or bilateral rhythmic coordination activities could favor the recovery of paretic limbs.

- Task-specific training on activities of the daily living seems to benefit patients with neurological damage more than general exercise in terms of improving daily functioning.
- Task-oriented learning should be supplemented by exercises to build muscle strength and increase endurance, in patients with neurological injuries.
- Muscle strength, increase of endurance and balance combined with proprioception training could improve functional abilities and general fitness in elderly people.
- People with motor deficits might benefit from interventions that augment plasticity, that promote dynamic motor skills learning and patients' motivation, and strategies that employ feedback.

1.1.3. Functional assessment of physical training

Extensive studies have evaluated the effects of virtual reality as a rehabilitation tool. Functional assessment metrics have been used to determine whether these technologies achieve greater physical improvement. This section lists the functional assessment metrics most used in clinical practice.

Motor ability scales or ADL tests

- **Fugl-Meyer Test of Motor Recovery (FMT) or Fugl-Meyer Assessment (FMA):** This test is a stroke-specific, performance-based impairment index. It is designed to assess motor functioning, balance, sensation, and joint functioning in patients with hemiplegia (Fulg-Meyer, Jassko, Leyman, Olsson, & Steglind, 1975) (Mugl-Meyer & Jaasko, 1980). It includes items assessing movement, coordination and reflex action of shoulder, elbow, forearm, wrist, hand, hip, knee, and ankle.
- **Common Object Test (COT)**: (Thrope, Stroh, & Baco, 1989) This scale aims to evaluate the use of functional nerve stimulation in people with tetraplegia. The COT test stablished a task analysis approach to evaluate the ability to perform specific phases of an activity.
- **Functional Independence Measure (FIM)**: (Hamilton, Laughlin, Fiedler, & Granger, 1994) This scale provides an assessment of severity of patient disability. The FIM has 18 items, concerning self-care, sphincter control, mobility, locomotion, communication, and social cognition, and each of them is scored on a seven-point scale, being 1= total assistance to 7= total independence.
- **Arm Motor Ability Test (AMAT)**: (Kopp, et al., 1997) This test evaluates

the deficits in ADL for patients with stroke by providing a qualitative and quantitative assessment of ADL. The test consists of 17 tasks of ADL activities such as preparing a sandwich. The function and the quality of movement of each task are measured by a 0-4 scale, being 0=no use and 4=almost normal use.

- **Modified Ashworth Scale (MAS):** (Craven & Morris, 2010) This scale is a muscle tone assessment scale used to measure the muscle resistance during passive ROM. It is performed by extending the patient's limb from a position of maximal flexion to maximal extension. Then, the MAS is assessed while moving from extension to flexion and scoring the resistance with a 5-point scale (Bohannon R. W., 1997). The MAS scale is the current standard for spasticity assessment, and the most commonly used clinical tool to evaluate the efficacy of pharmacologic and rehabilitation interventions for patients with SCI.

Functional metrics in upper limb

- **Functional Reach Test (FRT):** It is a single item test developed for assessing the balance and stability in older adults by measuring the maximum distance an individual can reach forward while standing in a fixed position (Duncan, Studenski, Chandler, & Prescott, 1992). The modified version of the FRT requires the patient to sit in a fixed position.

- **Physical Capacities Evaluation of Hand Skill (PCE):** (Bell, Jurek, & Wilson, 1976) This test provides an objective measurement of performance in people with paraplegia, tetraplegia, and hemiplegia. It consists of 5 unilateral hand skill tests, 7 bilateral hand skill tests and a dynamometer reading, and the whole test can be performed either with or without an orthosis. The items are timed tasks or a specific period for task completion.

- **Wolf Motor Test (WMT):** It quantifies upper extremity motor ability through timed and functional tasks. The original version of the WMT was developed to examine the effects of CIMT in patients with stroke and traumatic brain injury (Wolf, et al., 2001). Afterwards, a graded WMT was developed by Uswatte and Taub to assess the motor abilities of patients who were functioning at a lower level (Morris, Uswatte, Crago, Cook, & Taub, 2001). The original version of the WMT consisted of 21 items, but the widely used version of the WMT consists of 17 items (Whitall, Savin, Harris-Love, & Waller, 2006).

- **Upper Extremity Function Test (UEFT):** The UEFT was designed primarily to quantify the patient's ability to execute upper extremity activities of a general nature, and does not take into consideration factors such as skill, speed, ROM, endurance and sensation (Carrol, 1965). The administration of the test consists of instructing the patient to be positioned comfortably in a chair in front of the table used for testing and evaluate their movements while performing different tasks.

- **Action Research Arm Test (ARAT)**: It is an observational measure to assess the upper limb function and motor recovery following cortical damage, described as a modification of the UEFT (Lyle, 1981). It assesses the patient's ability to handle objects differing in size, weight, and shape and therefore it is an arm-specific measure of disability (Platz, et al., 2005). This test consists of 19 items organized in four subcategories: grasp, grip, pinch, and gross arm movement, and the performance of each item is rated on a 4-point scale (McDonnell, 2008).

- **Nine-Hole Peg Test (9-HPT):** (Kellor, Frost, Silberberg, Iversen, & Cummings, 1971) It is an assessment of dexterity in healthy subjects and people with impaired dexterity. It is a single-item test that consists of a timed task that consists of placing nine pegs in a board and then remove them.

- **Box and Block Test (BBT):** (Holser & Fuchs, 1960) This test provides a generic measure of gross manual dexterity. It is a unilateral test in which wooden blocks have to be moved from one compartment to another of the box for 1 minute, and the number of blocks transported is the score of the test.

Functional metrics in lower limb

- **Timed Up and Go Test (TUG):** This test consists of getting up from a chair with armrests, walking 3 meters or 10 steps, turning to return to the chair, and sitting down. The evaluator measures the time spent. This test requires the subject to perform several potentially destabilizing movements. Although designed for use with the elderly, several studies evaluating subjects with stroke have used this test.

- **Berg Balance Scale (BBS)**: It was developed in 1989 as a quantitative measure of functional balance status of the elderly, reproducible and with a strong internal consistency (Wee, Bagg, & Palepu, 1999). It consists of 14 tasks that assess static and dynamic aspects of postural control. The items in each test are representative of daily activities that require balance on **one-leg stand with open eyes (OLS-O) or close eyes (OLS-C)**, with the person sitting, standing, bending and stepping. Some tasks are rated according to the quality of task performance, while others are evaluated by the time it takes to complete the task.

- **6-Minute Walking Test (6-MWT o SMW):** This test is a subscale used to evaluate endurance and **gait speed (GS)** in different populations with physical disabilities and in elderly people with disease. It consists of covering the greatest number of meters for 6 minutes walking at maximum speed. The distance of the corridor to be covered varies according to the authors (García Hernández, et al., 2021).

- **10 Meter Walk Test (10-**MWT): It is a performance measure to assess walking speed in meters per second over a short distance (Watson, 2002). It is often employed to determine gait and functional mobility. The 10-MWT consists of timing how long it takes the subject to run 10 meters at maximum speed without running.
- **30-Seconds Chair Stand Test (30S-CST):** It is also known as the 30 Second Sit to Stand Test (Jones, Rikli, & Beam, 1999). It was designed for testing leg strength and endurance in older adults. It is part of the **Fullerton Functional Fitness Test Battery** (Miotto, Chodzko-Zajko, Reich, & Supler, 1999) which was designed for use with community-dwelling older adults and includes the follow items: floor sit-and-reach, back scratch, 8-up-and-go, arm curl, 30-s sit to stand, 2-min step, and **9-minute walking test (9-MWT)**. The 30S-CST test was developed to overcome the floor effect of the five or ten repetition sit to stand test in older adults.

Table 1. Summary of upper and lower limb functional metrics with description of their primary assessment.

	Test	Assessment
Motor Ability	Fugl-Meyer Test of Motor Recovery, FMT-MR	Balance, motor ability, ROM (stroke)
	Common Object Test, COT	ADL (tetraplegia)
	Functional Independence Measure, FIM	Motor ability
	Action Motor Ability Test, AMAT	Motor ability, ADL
	Modified Ashworth Scale, MAS	Muscle tone, Spasticity
Upper Limb	Functional Reach Test, FRT	Balance, functional mobility (elders)
	Physical Capabilities Evaluation of Hand Skills, PCE	Hand dexterity
	Wolf Motor Test, WMT	Functional tasks, strength, movement quality (brain injury)
	Upper Extremity Function Test, UEFT	Functional ADL
	Action Research Arm Test, ARAT	Functional mobility, arm-specific
	Nine-Hole Peg Test, 9-HPT	Hand dexterity
	Box and Blocks Test, BBT	Gross manual function and dexterity
Lower Limb	Timed Up-and-Go, TUG	Balance and gait function
	Berg Scale	Balance
	One-Leg Standing open eyes, OLS-O One-Leg Standing close eyes OLS-C	Balance
	9-Minute Walking Test, 9-MWT	Gait function and endurance
	6-Minute Walking Test, 6-MWT, SMWT	Gait function and endurance
	10-Meter Walk Test, 10-MWT	Gait function
	Gait Speed, GS	Gait function
	30-Seconds Chair Stand Test, 30-SCST	Strength and endurance
	Fullerton Functional Test	Strength, flexibility, endurance

1.2. Virtual reality technology

New treatments have significantly expanded the panel of therapeutic and rehabilitation strategies. These treatments include constraint-induced movement therapy (CIMT) (Morris, Taub, & Mark, 2006), treadmill training with partial weight-bearing (Turrolla, et al., 2013), robot-assisted therapy (Ribera & DeSouza, 2014) (Chang & Kim, 2013), and virtual reality (VR) based interventions. Among all, this section focuses on describing the characteristics of VR-based interventions as the current application of VR training (VRT) for upper and lower limb physical rehabilitation.

1.2.1. General concepts of virtual reality

In recent decades, the adoption of low-cost computer technologies focused on monitoring movements and simulating realistic environments for personalized activities has been increasing (Keshner, Weiss, & Geifman, 2019). So-called immersive technologies have emerged that include the three types of extended realities, as well as exergames. Extended realities consist of virtual reality, mixed reality, and augmented reality. Augmented and mixed reality technologies allow the superimposition of layers of digital information over real space, taking advantage of real information and projecting digital elements. Augmented reality is supported on devices such as smartphones, tablets or viewers with cameras and minimizes the need for motion calibration and visuomotor transformation that is usually required to interact in a virtual environment (Levin & Demers, 2021). Currently, mixed reality is considered a subtype of augmented reality that does allow basic interaction with these augmented elements and, therefore, mixed reality integrates the visuomotor transformations necessary to enable this function. In contrast, virtual reality technology is a computer-generated three-dimensional digital environment (Oujamaa, Relave, Mottet, & Pelissier, 2009) that is distributed on visual-auditory devices. The user can experience the virtual environment (VE) as if it were real and can interact with it using standard peripheral devices or multimodal devices such as gloves or haptics.

Virtual reality differentiates between two categories, immersive and non-immersive reality. The former refers to a type of VR in which the screen encompasses the users' entire field of view and allows users to fully immerse themselves in the VE using systems such as Head-Mounted-Display (HMD) equipment or a system based on projection onto a cube-shape VR room such as a CAVE (Cave Automatic Virtual Environment) (Huygelier, Schraepen, Van Ee, Vanden Abeele, & Gilleber, 2019). However, a VR-non-immersive environment refers to the less immersive application of the technology and is usually distributed in a flat screen or 2D environment (Lee, Wonjae, & Seungwon, Development of an 360-degree of virtual reality video-based immersive cycle training system for physical enhancement in older adults: a feasibility study., 2021). This non-immersive reality is also referred to as augmented virtuality, as it is not a first-person but a third-person experience, where the user's movements and actions are replicated by an avatar that is projected into the digital environment through a 2D screen. In general, immersive VR provides a more realistic motor sensory experience for the user as it has no temporal or spatial limitations and therefore is said to respect motion fidelity (Huygelier, Schraepen, Van Ee, Vanden Abeele, & Gilleber, 2019).

Fully immersive virtual reality devices or HMDs can be classified according to two characteristics: the degrees of freedom (DOF), the use of external hardware or the motion sensing system. Degrees of freedom refer to the amount of motion the device can measure. The most limited ones only detect 3 degrees of freedom of user rotation as well as orientation in space. While those that detect up to 6 degrees of freedom add to the 3 degrees of freedom of rotation the 3 degrees of freedom of translation, thus being able to detect the translations in the 3 axes. Regarding the use of external hardware, an HMD is dependent or independent based on whether it requires some external device or hardware to perform motion detection calculations. In the case of the dependent or 'outside-in tracking' HMDs, the sensors are external to the device and are placed in a stationary location.

Table 2. Classification of commercial VR HMDs.

	3DoF	6DoF
Dependent **(Outside-in tracking)**		Oculus Rift S HTC Vive Pro 2/ Pro Eye PlayStation VR2 HP Reverb G2 Samsung HMD Odyssey Valve Index Windows Mixed Reality Pimax Vision 8K Varjo Aero
Independent **(Inside-out tracking)**	Google Daydream Samsung Gear VR	HTC Vive Focus 3 / Cosmos Elite Oculus Quest 2/Oculus Quest Pro Lenovo Mirage Solo

Moreover, these HMDs require a console, computer or processing station to which be in communication, either through a cable or wirelessly, to get the orientation and positioning information. Nowadays, the currently available VR HMDs on the consumer market (see Table 1) are supported by 6 DOF tracking and are usually based on embedded infrared systems, as is the case with Oculus Rift (Farahani, et al., 2016) or the Lighthouse stations (Dempsey, 2016) that are typically used with HTC Vive and other SteamVR-based headsets.

These systems provide a very precise tracking of both position and orientation. Despite the positive outcomes in position and orientation tracking of these systems, they still must deal with two main problems: first, the reduced tracking areas limit the person's movement space and activities; and second, the loss of tracking or changes in height measurements along the tracking space can cause incorrect measurements of the orientation of the device (Niehorster, Li, & Lappe, 2017). For these reasons, several alternatives have been brought up to improve this setup. For example, the inside-out tracking of independent HMDs uses infrared cameras that are mounted on the headset itself to scan the environment (Passos & Jung, 2020). Even though these tracking systems have shown a slight decrease of accuracy and highly dependence on the environmental conditions, they allow the user to move freely. Commercial devices classified according to these two characteristics are shown in Table 1.

1.2.1. Virtual reality terminology

Along with virtual reality technology both the concepts of immersion and a sense of presence arise. We use the term **immersion** to reflect the user’s engagement that a computer-based simulation achieves to better represent reality. This engagement is achieved because of the use of equipment with certain technical characteristics, such as the use of involving systems with panoramic view, displays with rich resolution, multimodal devices that allow more natural interaction with physical fidelity to the movement (Slater, 2018). While the concept of **sense of presence** was defined by Witmer and Singer as “a psychological state of “being there” mediated by an environment that engages the users’ senses, captures their attention, and fosters their active involvement” (Witmer & Singer, 1998). Sense of presence is influenced by the physical awareness of the display, internal factors, social factors and emotions. In fact, these authors developed the most used metric for evaluating the effectiveness of VEs to promote the sense of presence. Nevertheless, there are other metrics based on user feedback in addition to the Presence Questionnaire (PQ) (Witmer & Singer, 1998), such as the Slater-Usoh-Steed Questionnaire (Slater M. S., 1995) and the Igroup Presence Questionnaire (Schubert, Friedmann, & Regenbrecht, 2001).

It is well-known that the mismatch between the visual stimulus and the lack of vestibular stimulation could cause **cybersickness** (La Viola Jr, 2000), which is a type of motion sickness that brings up a set of symptoms such a fatigue, drowsiness, disorientation, postural instability, sweating, headaches, eye strain, a stomach awareness or nausea (La Viola Jr, 2000). This type of sickness can occur during and/or after exposure to VE due to the device characteristics (e.g., field-of-view, frame rate, resolution, or head tracking) or the lack of habituation to the technology (Melo, Vasconcelos-Raposo, & Bessa, 2018). The manifestation of these symptoms compromises the usability of the VE and negatively affects the sense of presence (Witmer & Singer, 1998). To evaluate the cybersickness using subjective questionnaires, the Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane, Berbaum, & Lilienthal, 1993) can be used. Related to the own perception of movement and proprioception in the VE comes the concept of **embodiment** or body-agency whenever the person is represented by a virtual avatar. The "sense of having a virtual body and being able to control it inside the VR context" is defined by literature as the sense of embodiment (Kilteni, Groten, & Slater, 2012). Therefore, when a user is partially or fully self-represented with an avatar in first-person in the VE there is an intention to provide them with this sense of embodiment. To evaluate virtual embodiment, the Virtual Embodiment Questionnaire (VEQ) (Roth & Latoschik, 2020) is often used. Self-representations affect the cognitive level imbuing spatial perception and interaction, cognitive fidelity, and realism (Gonçalves, Melo, Barbosa, Vasconcelos-Raposo, & Bessa, 2022). But it also has an influence on the sense of presence in the regard of credibility.

Moreover, virtual reality technology maintains fundamental aspects of video games, such as user motivation through appropriate gamification strategies and, of course, socialisation. Virtual or **remote socialization** has proven to be a key factor in increasing time-spent playing games (Jansz & Tanis, 2007). Social competition or scoreboards help to maintain the self-esteem and **motivation**. It also allows for interaction with a partner who can share feedback and encouragement. To evaluate the amount of social interaction and its quality among co-player, the Interpersonal Interaction Questionnaire for Observers (IPIQ-O) (Goršič, Clapp, Darzi, & Novak, 2019) is used. Furthermore, the Intrinsic Motivation Inventory (IMI) (Ryan & Deci, 2000) can be used to measure genuine motivation resulting from the performance of activities.

Finally, one of the most evaluated characteristics of any novel virtual reality system or experience is its usability. The concept of **usability** is traditionally understood as the user's expectation when using a technology and was related to the design, aesthetics, and ease of manipulation of devices or software tools. Usability evaluations range from determining the acceptance of a system to the perceived enjoyment of using it, or even the perceived usefulness. In virtual reality, the *gold-standard* questionnaire for usability evaluation is the System Usability Scale (SUS) (Brooke, 1996). From the point of view of perceived usefulness, the Credibility and Expectancy Questionnaire (CEQ) (Deviilly, Grant, Borkovec, & Thomas, 2000) is used.

1.2.2. Principles of virtual reality in physical rehabilitation

There is a prolific literature on serious games and their potential to increase patient motivation, learning through task repetition in an enriched environment and confidence gained through positive reinforcement and immediate feedback (Jato, Cole, Bradlyn, & Pollock, 2008). To these aspects, it should be added the gamification strategies and the capacity for social interaction that can be implemented in these applications allowing to enhance active participation, increase adherence (Park, et al., 2020) and self-management of the therapy (Fitzgerald, et al., 2004). The rehabilitation-motivation approach of exergames is a psycho-social model that embraces the readiness of the participant to be an active agent in the rehabilitation process. Therefore, many serious games encourage the person's action throughout (Lohse, Shirzad, Verster, Hodges, & Van der Loos, 2013) the implementation of goal-directed behaviour strategies. This evidence recognized in serious games can be extrapolated to exergames based on virtual reality technology for physical recovery purposes (Levin, 2011). In fact, several studies point out that the application of exergames in physical therapies increases the engagement of the elderly (Subramanian, Dahl, Skjæret Maroni, Vereijken, & Svanæs, 2020) and improves cognitive function in patients with mild cognitive impairment (Amjad, et al., 2019).

Based on these claims, it seems that the use of virtual reality could better the neuroplasticity in the damaged nervous system (Burridge & Hughes, 2010) in physical therapies. Virtual reality training (VRT) is a type of exergame intervention that is developed to simulate a VE designed specifically for therapeutic purposes (Liu, et al., 2022) and that integrates training protocols and visual feedback to provide an interactive and immersive experience (Chen, Zhang, Guo, Bao, & Zhou, 2021). Some authors define VRT as "the use of interactive simulations created with computer hardware and software to offer users to participate in environments that look and feel similar to real-world objects and events" (Weiss, Kizony, Feintuch, & Katz, 2006). Therefore, proposing engaging exercises that are motivating to the target population (Laufer, Dar, & Kodesh, 2014) can simultaneously strengthen muscles, sensory response and lead to increased attention, motor control and gait efficiency (Lee & Shin, 2013) (Moreira, Rodacki, Costa, Pitta, & Bento, 2021). After all, virtual rehabilitation offers the opportunity to create an experience that incorporates augmented feedback, facilitating cortical plasticity through guided practice.

Few recent systematic reviews (Hatem, et al., 2016) indicate that there is moderate-quality scientific evidence that virtual reality technology is similar to standard rehabilitation treatment in terms of recovery from upper limb impairments and disabilities (Laver, George, Thomas, Deutsch, & Crotty, 2011)

(Pollock, et al., 2014). Studies in computational neuroscience have shown that VR technology improves learning and motor task performance due to the feedback on movement characteristics it provides (Turrolla, et al., 2013). However, recent reviews of the field concluded that VR treatment per se achieves no better effects than conventional treatment in the recovery of motor functions of gait function, balance, cognitive functions, and activities of daily living (Laver, George, Thomas, Deutsch, & Crotty, 2011). In contrast, there is moderate quality scientific evidence that VR combined with other rehabilitation treatment is superior to other rehabilitation treatment alone (Turrolla, et al., 2013) (Lee & Chun, 2014). These results are especially relevant in stroke patients. Thus, the combination of virtual reality with another rehabilitation treatment seems to be valuable and could be integrated as an adjuvant therapy in motor rehabilitation strategies.

1.3. Virtual reality training

Despite the effort of many authors to differentiate between fully immersive VR systems and non-immersive VR systems (see Figure 3) the term "VR" is still used indiscriminately to refer to both. This ambiguity contaminates the search criteria for novel fully immersive VR. Beyond this issue, a prolific scientific literature can be found on fully immersive VR systems. Most of the scientific contributions cover design principles and intervention strategies that have been validated in a population with motor disabilities due to neurological damage. The effects of VR for functional rehabilitation are often assessed by the functional metrics described in section 1.1.3.

In this section we have collected the most relevant studies of VRT for bimanual functional training and functional training of activities of daily living in the upper limb. Equivalently, it is included the most relevant studies of VRT for functional training of the lower limb, particularly focused on pedalling activity. We have included a comprehensive description of the intervention’ strategy and the functional assessments applied in each study. Thus, most used functional metrics in VRT functional validation studies are briefly described below.

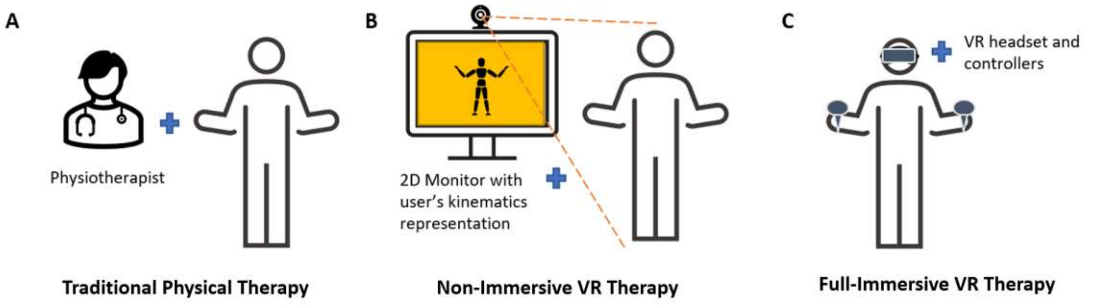

Figure 3. Physical therapy modalities and their required resources or equipment: A) Conventional or traditional physical therapy (TPT), B) Non-Immersive VRT and C) Full-immersive VRT.

1.3.1. Upper limb solutions for ADL training in virtual reality

The areas covered in upper limb motor rehabilitation with VR focus on spatial task training and perceptual-motor training which in some cases presents a suitable approach to functional ADL training (Holden, Dyar, & Schwamm, 2005). Overall, studies dedicated to VR treatment in the recovery of motor, and ADL functions indicate that the VR approach produces better motor and functional outcomes than conventional therapy (Turrolla, et al., 2013). However, many published studies consist of small experiments that aim to enhance manual dexterity, often combining haptics. These studies are still conducted with small groups of participants (Turrolla, et al., 2013), making it difficult to generalize conclusions to consolidate scientific evidence of their effectiveness (Gil-Agudo, et al., 2013).

The most recent studies, reported in systematic reviews and meta-analyses of the state of the art conducted (Karamians, Proffitt, Kline, & Gauthier, 2020) (Domínguez-Téllez, Moral-Muñoz, Salazar, Casado-Fernández, & Lucena-Antón, 2020) indicate that on average VR interventions can produce a 28.5% improvement in maximal physical recovery (Karamians, Proffitt, Kline, & Gauthier, 2020). In contrast to studies carried out in the past decade, the conclusions of these studies pointed out that VR-based rehabilitation may be more effective than conventional methods. These findings raise the possibility that the new systems and designs are more effective than those observed in previous studies.

Among the studies evaluating autonomy in ADL acquired after the application of VRT, Piron *et al.* (Piron, et al., 2005) found that the results of this intervention produced significant improvements over baseline Fugl-Meyer and FIM measurements. The Fugl-Meyer score correlated significantly with the duration and speed of reaching movements, indicating that improved motor recovery may benefit from extrinsic feedback provided by the virtual environment. These assertions are revalidated by another study (Turrolla, et al., 2013) also focused on stroke patients. The analysis of the results indicated that both groups; VRT and traditional physical training (TPT), significantly improved the Fugl-Meyer Upper Extremity and FIM scores with respect to the initial measurement, but the improvement obtained in the VRT group was significantly greater than that obtained by the TPT group. Shin, *et al*. (Shin, Ryu, & Jang, 2014) carried out two clinacal trials with the VR platform called RehabMaster™. The first was an observational with 7 post-stroke patients using RehabMaster™ 30 minutes twice a week for two weeks. And the second study was a randomized controlled trial of two groups of patients with stroke who received 10 sessions of 20 minutes of VRT or TPT. In this second case, the FMA, Modified Barthel Index (MBI) and adverse effects were measured. From the first trial it was reported that the intervention improved the Fugl-Meyer assessment and the MBI across evaluation times, while the results from the second trial revealed that the addition of RehabMaster™ intervention tended to enhance the improvement in the FMA but did not affect the improvement in the MBI and no adverse effects were reported. Moreover, Kwon *et al*. (Kwon, Park, Yoon, & Park, 2012) studied the effects of TPT combined with VRT versus TPT on upper limb function and ADL in post-stroke patients. Trial outcomes revealed that even though the TPT group and the intervention (VRT+TPT) group significantly improved the ADL performance, only the intervention group showed significant improvement on FMA and WMT. Hence, it can be affirmed that immersive complementary virtual reality systems have a significant improvement effect on functional rehabilitation in ADL.

The most recent studies end up drawing similar conclusions. A small study of 12 patients with stroke who performed 10 sessions with HMD VR for upper limb strengthening evaluated the feasibility of this therapy (Lee S. H., 2019), The primary efficacy of this intervention was demonstrated by the significant functional improvement in all outcome measures (ARAT, Box-and-Block Test and MBI) after training. However, the small number of study participants and the lack of a control group limit the extrapolation of these conclusions. Another study carried out in a larger sample (30) of patients with stroke (Ahmad, Singh, Mohd Nordin, Hooi Nee, & Ibrahim, 2019) evaluated the functional metrics FMA-UE, WMT for both VRT and TPT groups. After an intervention of 8 consecutive weeks the results of this study concluded that both groups had achieved an improvement in motor ability and equivalent sensory function.

Based on the idea of the motivation provided by these tools and their enhancement of adherence to treatment (Dias, et al., 2019), two lines of study of VRT in the upper limb have emerged. On the one hand, we find those studies that sought to analyze VRT systems for telerehabilitation and, therefore, allowed the user to train a wide variety of movements and a large number of repetitions. As an example, the MIT group (Hold en M. K., 2005) developed a VRT system for stroke patients, which allowed the design of meaningful therapeutic scenes for their patients with a wide variety of configurations within the context of functional or goal-directed tasks. Another study (Warland, et al., 2019) established the feasibility and acceptability of a modified version of a commercially available VR game (the Personalized Stroke Therapy system) for upper extremity rehabilitation with stroke survivors. Their results indicated a high level of enjoyment of the application by participants. They also reported a medium value of perceived physical exertion. On a smaller scale, we find a study of functional telerehabilitation (Lin, Kelleher, & Engsberg, 2013) that enrolled two participants with hemiparesis involved performing 1 hour of VRT per day for 6 weeks. At the end of the intervention the participants showed an improvement in functional mobility over baseline. Another research group (Adamovich, Merians, & Boian, 2003) employed their non-immersive virtual reality rehabilitation system combined with the commercially available haptic glove Cyberglove™ to provide haptic monitoring (Jack, Boian, Merians, & al., 2001) and feedback about hand kinematics. In this study of functional recovery of hand ADLs with post-stroke patients, VR treatment was combined with CIMT. The results obtained from the quantitative analysis of hand kinematics (ROM, speed, fractionation and work) and grip tasks indicated that they all had a fairly high degree of motor recovery.

On the other hand, there are studies in which the main motivation is to validate the solution as a diagnostic tool or for accurate movement assessment. To this end, analyses of the design characteristics of the feedback provided, the design of virtual environments and the validity of the proposed tasks are carried out. A research group on cognitive disabilities (Zhang, Abreu, Seale, & al., 2003) proposed an VR solution to test functional ADL abilities. This test consisted of performing a task divided into 81 subtasks, so that each receives a score that makes up the total rating. They validated with 54 participants with disabilities the reliability and validity of this tool, proposing it a posteriori as a reference for disability assessment in VR. Subramanian *et al.* (Subramanian, et al., 2007) compared the motor performance and movement patterns performed to reach 6 targets positioned in VE and in the physical environment using the CAREN[1] system. The objective was to identify whether the proposed design in VE managed to generate homologous movements than those performed in physical space by analyzing motion kinematics, aiming error and trajectory smoothness. The results obtained showed that the speed of movement in the virtual environment was lower and the movements in virtual reality were more rounded, but the accuracy of movement for target ranging was comparable in both environments. Finally, with the intention of proposing a method for the design of interactive environments (Cardona Reyes, Acosta Escalante, Áalvarez Rodríguez, Muñoz Arteaga, & Muñoz Zabala, 2015) brought an specific approach. They proposed a verified method for hand rehabilitation applications, based on models that allow the diagnosis of abilities or disabilities through occupational therapy. Lastly, the patent-pending TRAVEE system is dedicated to neuromotor rehabilitation after stroke (Moldoveanu, et al., 2019). This tool integrates several technologies: virtual reality, brain-computer interfaces, functional electrical stimulation, robotics, haptics and multimodal feedback.

Other non-immersive virtual reality systems based on the use of 2D displays with motion tracking systems (Dimbwadyo-Terrer, et al., 2015) (Cha, et al., 2021), commercial gaming devices combined with sensory stimulation systems (Gutiérrez, Sepúlveda-Muñoz, Gil-Agudo, & De los Reyes Guzmán, 2020) such as functional electrical stimulation (FES), or intrinsic feedback such as oculography based on brain computer interaction (BCI) (Lupu, Irima,

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[1] CAREN is a Computer Assisted Rehabilitation Environment, which is a CAVE-like solution designed for balance assessment and therapy, gait analysis, adaptability, and motor control, among others. (B.V., 2021).

Ungureanu, Poboroniuc, & Moldoveanu, 2018) (Teo, Muthalib, Yamin, & al., 2016) (Lupu, Botezatu, Ungureanu, Ignat, & Moldoveanu, 2016) have proven to be equally effective in motor rehabilitation or their effects are still being validated.

1.3.2. Lower limb solutions for gait function and cycling in virtual reality

Whereas the literature of VRT for upper limb often relies on *ad hoc* solutions to adapt the game to task-specific exercises, in the case of the lower limb, most of the VRT solutions focus on the locomotion task, and therefore we find three main activities which are balance, gait function and cycling. Nevertheless, scientific evidence on lower limb rehabilitation with fully immersive VR is not as comprehensive or systematic. For this reason, the most relevant findings in the field are presented below in three categories: upper limb rehabilitation, gait rehabilitation and cycling exercise for lower limb rehabilitation. These findings are respectively organized in Table 3, Table 4 and Table 5 at the end of the chapter.

VRT in balance and gait

Regarding gait-based studies, we found the following examples of fully immersive VRT solutions whose effectiveness has been evaluated in older adults' population by analysing standard functional metrics outcomes after applying a physical intervention using this VRT in one group of participants versus a control group using traditional TPT. As first example, the study of Yesilyaprak *et al*. (Yeşilyaprak, Yildirim, Tomruk, Ertekin, & Algun, 2016) focused on vestibular balance training, and the TPT group underwent balance training and VRT group used a VR-based balance exercises with sensory feedback. Both groups trained 35 to 45 minutes 3 days a week for 6 weeks. In this study, the functional metrics TUG, OLS-O, OLS-C were captured before and after the intervention. A similar work carried out by Rebelo *et al*. (Rebelo, de Souza Silva, Dona, Barreto, & de Souza Siqueira Quintans, 2021) who proposed balance training using the Oculus Rift with some commercial videogames. They defined an intervention of 2 sessions of 50 minutes each week along 8 week and the metrics measured were TUG and FRT. Another study (Phu, Vogrin, Al Saedi, & Duque, 2019) compared the effects of VRT versus TPT using the OTAGO exercise program on improving balance and physical performance. After 2 supervised sessions per week for 6 weeks they measured TUD, GS, OLS-C and OLS-O. Lastly, despite that Lee (Lee K. , 2020) applied similar design principles to the previous ones based on sensory feedback, they focused on gait training with virtual reality. In this case, it proposes a more intensive intervention of 5 sessions per week of 50 minutes duration, for 4 consecutive weeks. In the later study, the metrics assessed were TUG, FRT, OLS-O, y GS.

Lee (Lee K. , 2020) directly addresses gait function training, while the other two approaches (Rebelo, de Souza Silva, Dona, Barreto, & de Souza Siqueira Quintans, 2021) (Yeşilyaprak, Yildirim, Tomruk, Ertekin, & Algun, 2016) work on a specific aspect that influences gait but does not necessarily achieve improvements in gait function per se. Accordingly, there were found legitimate discrepancies in the results on mobility using TUG tests. Lee (Lee K., 2020) showed that VRT could improve participants' TUG compared to TPT. Also, Phu, *et al.* (Phu, Vogrin, Al Saedi, & Duque, 2019) observed that VRT and TPT showed significantly better improvement than non-intervention group in TUG, but only the VRT improved OLS-C and OLS-C. Nevertheless, the other two studies found that VRT could not improve participants' TUG compared to TPT. Even so, both Lee (Lee K. , 2020) and Rebelo *et al.* (Rebelo, de Souza Silva, Dona, Barreto, & de Souza Siqueira Quintans, 2021) reported intervention effects on FRT distance agreed on the lack of significant difference observed between VRT and TPT; the same conclusion was drawn from GS in Lee's study. Regarding OLS outcomes, Lee observed that VRT significantly improved OLS-O as compared to TPT, while for Yesilyaprak *et al*. (Yeşilyaprak, Yildirim, Tomruk, Ertekin, & Algun, 2016) there was no significant difference on OLS-C performance between VRT and TPT.

It is noteworthy to acknowledge that virtual gait training techniques allow users to explore VEs adapted to the real spaces and to track their locomotion movement in real time so as not to break the sense of presence of the experience. This requirement implies technological systems that can overcome these limitations of space and user tracking (Janeh & Steinicke, 2021). For this reason, the most common systems for this practice are walking-in-place interfaces, which allow the user to perform the strides without moving the body forward using unidirectional treadmills (Slater, Steed, & Usoh, 1995). Also the virtual treadmill, which is a naturaistic metaphor for navigation in immersive virtual environment. And finally, the redirected walking interfaces, which allow the user to explore a considerably wider virtual world than the real world (current physical space available) (Steinicke, Bruder, Jerald, Frenz, & Lappe, 2009), since the VE presents a slight variation from the path walked by the user (Nilsson, et al., 2018). The later approach requires novel omnidirectional treadmills such as the so-called CyberWalk™. This omnidirectional treadmill allows natural walking in any direction and at any arbitrary scale in the virtual environment, but it is an extremely expensive system to maintain (Souman, et al., 2011).

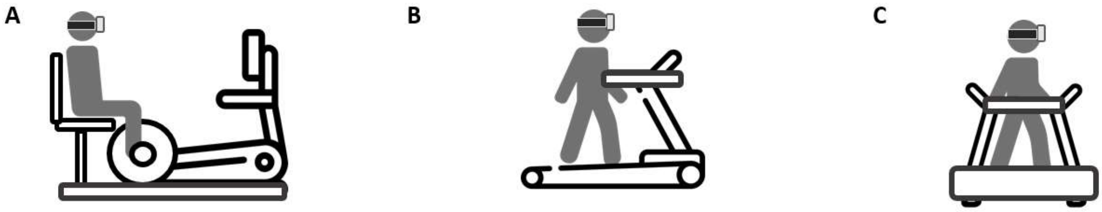

Figure 4. Treadmill locomotion interfaces: A) seated, B) unidirectional, C) Omnidirectional treadmill.

VRT in cycling

An alternative to the lower limb gait exercise is the cycling exercise since the use of leg-ergometers or static-bikes is affordable for patients and simple to use. In fact, several studies have confirmed that the practice of pedalling exercise with visual feedback could improve neuromuscular control (Song, Kim, & Kim, 2004) and overall performance (Grani & Bruun-Pedersen, 2017) (Yang, et al., 2014). In addition, understanding the context of patients who suffer motor disability due to a sudden injury start rehabilitation with a very limited mobility condition, so they do not have sufficient strength or cannot tolerate intense gait training (Katz-Leurer, Ofer Keren, & Dvir, 2006). Therefore, the pedalling activity is suitable in these cases because at the same time they strengthen the lower limb musculature, the cycling activity acts as a pseudo walking task-oriented exercise (Kautz & Brown, 1998). As bilateral training improves inter- and intra-limb timing parameters which are major parameters for balanced standing or walking. In fact, Katz-Leurer *et al.* study (Katz-Leurer, Ofer Keren, & Dvir, 2006) stated that cyclo-ergometer pedalling exercise in stroke patients can improve their motor skills and balance more than if they perform conventional rehabilitation without including this activity.

Assuming the mentioned potential benefits of cycling exercise, it is hypothesized that augmented feedback with extrinsic data can enhance the recovery outcomes and increase motivation (Grani & Bruun-Pedersen, 2017). Quite few studies have focused on the analysis of functional metrics in virtual pedalling. In a recent study (Yin, Hsueh, Yeh, Lo, & Lan, 2016) evaluated the functionality of VR-cycling training applied to 10 stroke patients to assess the improvement of the bilateral asymmetry between the experimental group and the control group after the VR-cycling intervention program. To evaluate this index, they equipped the ergometer pedals with force plates to determine the effect of the VR-cycling training on each limb. The improvement of bilateral strength and standing balance showed significant difference between VR-cycling training and TPT. Similarly, a previous study (Yang, et al., 2014) compared the effects of a cycling training with extrinsic biofeedback with no-immersive interface and TPT on lower limb functional recovery, walking endurance, walking speed and muscle spasticity in patients with stroke by assessing the FMA, 6MWT, 10MWT and MAS after a 4 weeks-intervention programme consisting of 5 session (of 30 minutes training) per week. The results showed that improvements in the VRT were significantly better than TPT in the FMA, 6MWT, 10MWT, and MAS scores.

There are studies focused on validating aspects of validity of use of their own solutions. In this way, aspects such as usability (Ferreira, Coimbra, Crisóstomo, & Liu, 2020) (Pedroli, et al., 2018) (Høeg, et al., 2021) acceptance (Grani & Bruun-Pedersen, 2017), sense of presence (Deutsch, et al., 2014) (Pedroli, et al., 2018) and the presence of adverse effects such as cybersickness (Pedroli, et al., 2018) (Lee, Choi, & Lee, 2021) (Høeg, et al., 2021) that the user may experience during the session have been evaluated. As a general pattern, all of them have explored these aspects for VR-cycling training solutions concluding positive evaluations in most cases. From this we can deduce the wide potential of using these approaches for motor disability rehabilitation. Overall, the challenge lies in generating a feasible technological proposal, homologous to gait rehabilitation with treadmills.

Currently, VRT-cycling systems found in the scientific literature typically employ high-cost robotic systems, such as ergometers or exercise bikes, and complex and highly specialized VR equipment. The most common solutions range from hardware modifications of commercial monocycles instrumented with inertial sensors (Cardoso, et al., 2019) (Høeg, et al., 2021) to developing a fully motorized pedal system (Ferreira, Coimbra, Crisóstomo, & Liu, 2020). These hardware solutions aimed to measure pedal cadence and to transmit this rotational data of the pedals to the virtual reality application via CAN communication using a CPU as intermediate node (Brunn-Pedersen, Pedersen Kasper, Serafin, & Kofoed, 2014) (Grani & Bruun-Pedersen, 2017). On the other hand, there are systems that, although they use a static bicycle, require motion capture equipment placed on the participant, or optical systems based on computer vision applications for tracking and visualizing the posture and movement of indoor cycling (Bini, Gil, Santiago, & Moura, 2021) (Kaplan, Yamamoto, Taketomi, Plopski, & Kato, 2019).

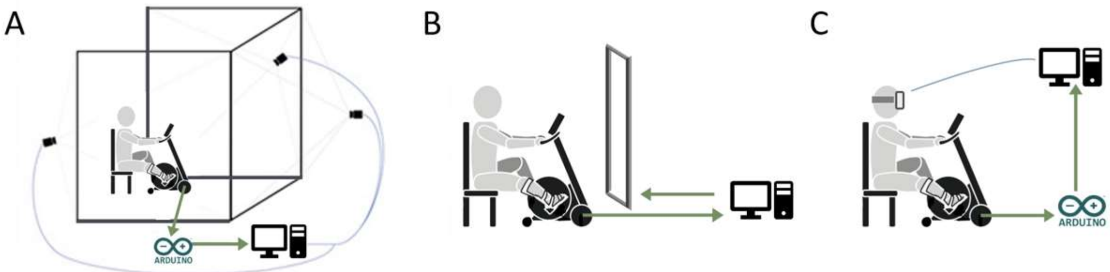

Figure 5. Virtual cycling interfaces: A) CAVE system, B) non-immersive system with *adhoc* ergometer, C) immersive system with *adhoc* ergometer.

1.3.3. Conclusions

From the review of the state-of-the-art and the categorization of the studies, the following main conclusions are drawn. Firstly, it is undeniable that the number of studies in motor rehabilitation with full-immersive VR is higher in the upper limb than in the lower limb. This fact can be attributed to the fact that upper limb training may not involve locomotion or displacement, which facilitates the adoption of VR. In addition, a substantial number of functional activities of daily living are based on bimanual coordination, manual dexterity and motor control of the upper limb. However, there are very few VR platforms for bimanual training, as most systems work on each arm independently.

The extensive literature in this field consistently shows that the use of VR in therapy achieves larger functional improvements (FMA, FIM) and greater range of motion (ROM) than those achieved by TPT (see Table 3). And the main driver is the input of motivation and gamification of the therapy sessions with VR, which leads users to exercise more frequently or intensely the target movements. It is worth noting that the studies reporting greater functional improvements in the VRT group compared to the TPT group applied PA interventions with more than 20 sessions over a time span of 3 to 6 weeks. Other studies that have reported equivalent improvements proposed a looser PA intervention. Therefore, the effect of user engagement through the use of VR is likely to have been blunted over time or not achieved at all.

Studies of full-immersive VR solutions for gait training showed an increase in balance ability using clinical measures (OLS-O) after the training period. Interestingly, this improvement in balance does not transfer to an improvement in gait, despite the correlation between balance and gait function. Nevertheless, these solutions are not specifically designed for gait activity but for stepping exercises or movement coordination. Then, it is noticeable the lack of full-immersive VR solutions focused on gait exercise.

From a scientific-clinical point of view, studies on total immersion VR solutions for pedal exercise training showed an increase in balance ability by clinical measures (Balance control, Standing Balance), gait performance (6MWT, 10MWT) and functional performance (FMA, Bilateral pedal force). Again, the studies in which physical improvement of VRT versus TPT is found are those in which the PA intervention have a high intensity. From a scientific-technical point of view, most of the VR-cycling platforms developed for this purpose usually modify the pedalling equipment to communicate the pedal to a computer that processes the information and renders a VE. All these studies have shown a high appreciation in terms of usability (SUS), low risk of motion sickness (SSQ), and the intrinsic motivation of these platforms.

Table 3. Comparison between effects of exercise intervention with full-immersive VR and traditional physical training on improving upper limb function. Outcomes' symbols: ↑=VRT achieves greater improvement; ↔ =VRT achieves equal improvement as TPT.

References	Intervention	Procedure	Design principles	Outcomes
Piron, *et al.*, 2005	**VRT**: ADL functional exercises with VR	5 session per week for 4 weeks	Extrinsic feedback related to task performance	FMA ↑ FIM↑
Turrolla, *et al.*, 2013	**VRT**: upper limb functional exercises with VR **TPT**: upper limb functional exercises	2hours/session; 5 sessions per week; for 4 weeks	Extrinsic feedback related to task performance	FMA ↑ FIM↑
Shin, Ryu, & Jang, 2014	**VRT**: upper limb functional exercises with VR system, RehabMaster™ **TPT:** upper limb functional exercises	10 sessions of 20 minutes	Extrinsic feedback related to task performance	FMA ↑ MBI↔
Kwon, *et al.*, 2012	**VRT+TPT**: ADL functional exercises with VR **TPT:** ADL functional exercises	30 minutes sessions; 5 sessions per week; for 4 weeks	Extrinsic feedback related to task performance	FMA ↑ WMT ↑ ADL performance ↔
Lin, Kelleher, & Engsberg, 2013	**VRT**: upper limb functional exercises	1 hour of daily session for 6 weeks	Extrinsic feedback related to task performance	Functional mobility ↑
Adamovich, Merians, &	**VRT+TPT**: upper limb functional exercises using non-immersive VR with haptics,	2 hours per session; 4-5 sessions per	Visual and haptic feedback related to	ROM↑

Boian, 2003	CyberGlobe™, combined with CIMT	week; for 3 weeks	performance task	Speed↑ Workload↑
Ahmad, Singh,, Mohd Nordin, Hooi Nee, & Ibrahim, 2019	**VRT+TPT**: standard physiotherapy sessions and functional exercises with VR **TPT:** standard physiotherapy sessions	2 hours per session; 1 session per week; for 8 weeks	Extrinsic feedback related to task performance	FMA ↔ WMT↔
Lee, S. H., 2019	**VRT**: upper limb functional exercises	30 minutes per session; 2-3 times a week; a total of 10 sessions	Extrinsic feedback related to task performance	MBI↑ ARAT↑ Box-and-Block Test↑

Table 4. Comparison between effects of exercise intervention with full-immersive VR and traditional physical training on improving gait and balance. Outcomes' symbols: ↑=VRT achieves greater improvement; ↔ =VRT achieves equal improvement as TPT.

References	Intervention	Procedure	Design principles	Outcomes
Yeşilyaprak, et al. 2016	**VRT**: VR-based balance exercises **TPT**: Balance training	Sessions of 35-45 minutes; 3 days/week; 6 weeks	Sensory feedback related to the task	TUG↔ OLS-C↔; OLS-O ↔
Lee K. , 2020	**VRT**: Gait training with VR **TPT**: Gait training	Sessions of 50 minutes; 5 days/week; 4 weeks	Visual feedback related to gait	OLS-O↑ TUG↑ FRT↔ GS↔
Rebelo, et al., 2021	**VRT**: Oculus Rift & commercial games **TPT**: Balance training	Sessions of 40 minutes; 3 days/week; 8 weeks	The task difficulty was gradually increased	OLS-O↑ TUG↔ GS↔
Phu, et al., 2019	**VRT**: VR-based balance & strength training **TPT**: OTAGO Balance & strength training	Sessions of 60 minutes; 2 days/week; 6 weeks	The task difficulty was gradually increased	TUG↔ GS↔ OLS-O↑; OLS-C↑

Table 5. Outcomes of cycling training with full-immersive VR Outcomes' symbols: ↑=VRT achieves greater improvement; ↔ =VRT achieves equal improvement as TPT.

References	Procedure	Design principles	Outcomes
Cardoso, et al., 2019	8 subjects with hemiparesis performed a single test at 60 rpm speed	Knowledge of performance feedback to maintain the cycling cadence at a target speed	No relevant conclusions regarding functional effects or system feasibility
Yin, et al., 2016	9 patients with stroke participated in the cycling exercise intervention. Sessions of 1 hour, 5 times a week for 2 weeks. Additionally, the VRT group (n=6) underwent 15 minutes of non-immersive VR cycling each time. TPT (n=3)	VRT: Sensory feedback related to the task	(VRT vs. TPT) Standing balance ↑ (VRT vs. TPT) Bilateral pedal force ↑
Yang, et al., 2014	31 patients with stroke participated in a cycling training intervention of sessions of 30 minutes, 5 times a week for 4 weeks. Participants were divided in 2 groups: TPT (n=16) and VRT (n=15), with MOTOmed™ and non-immersive feedback system	VRT: Sensory feedback related to the task	(VRT vs. TPT) FMA↑ (VRT vs. TPT) 6MWT↑ (VRT vs. TPT) 10MWT↑ (VRT vs. TPT) MAS↑

Ferreira, et al., 2020	8 healthy subjects performed 12 tests of 1 minute each, at 3 different speeds: 600 rpm, 1300 rpm and 2000 rpm; and 4 levels of resistance: 0, 0.2, 0.4 and 0.7	Knowledge of performance feedback to maintain the cycling cadence at a target speed	SUS = 74.4%
Lee, et al., 2021	5 healthy older adults performed a single test of 20 minutes cycling exercise	Sensory feedback related to the task	SUS = 94.60% SSQ-after-exposure=2.24
Pedroli, et al., 2018	5 healthy older adults performed a single test of 15 minutes cycling exercise	Knowledge of performance (auditory) feedback to maintain the cycling cadence at a target speed	SUS=76.88% SFSS = 4.33
Song, et al., 2004	20 healthy subjects participated in a repeated training (3 repetitions each session for one week) by riding the non-immersive virtual system combined with an unfixed bike under 2 conditions: with or without visual feedback	Knowledge of performance feedback to keep the balance (weight shift) and to maintain the balance cycling cadence at a target speed	Balance control ↑ with visual feedback Weight shift control ↑ with visual feedback Cycling speed control ↑ with visual feedback
Høeg, et al., 2021	11 older adults participated in a co-player session of 10-15 minutes cycling exercise with MOTOmed™ and Oculus Rift	Sensory feedback related to the task	SUS= 85% IMI: Enjoyment= 6.5; Effort/Importance=6.4; Relatedness=6.3. SSQ: Nausea=16.5; Oculomotor=5.5;

Disorientation=6.3; Total =8.5.

VEQ: Ownership=5.6; Agency=5.6; Change= 2.5

IPI: Conversation=3.2; Balance=2; Valance=4.2; Game relatedness= 4.5; Overall mood=4.3

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CHAPTER 2: HYPOTHESIS, GOALS AND SCOPE

2.1. Hypothesis

The main hypothesis of this thesis is that the use of virtual reality solutions as a therapeutic complement to traditional rehabilitation programs in people with motor disabilities could achieve greater motivation and adherence to physical activity programs. Furthermore, this adherence could imply a functional improvement. This hypothesis applies to both upper and lower limb rehabilitation strategies. Thus, for lower limb training the following secondary hypotheses are defined:

H1: A simple setup based on capturing hip flexion-extension motion during pedalling activity is sufficient to generate an engaging virtual reality solution.

H2: A rhythmic therapy strategy with a visual queue allows the user to maintain the pedalling cadence.

H3: The use of this virtual reality platform is considered to be a valuable tool for the functional recovery of patients with LLD.

H4: Elderly people accept virtual reality technology as a tool for pedalling physical activity and they are satisfied with its use.

Regarding upper limb training, the following secondary hypothesis are hereby defined:

H5: A novel system that a) uses off-the-self low-cost hardware VR device combined with b) a specifically designed VR game can be a cost-effective solution for tele-rehabilitation.

H6: The creation of a virtual reality game for bimanual upper limb rehabilitation should be based on a virtual environment design guideline.

2.2. Goals

The overall objective of this thesis is to evaluate the feasibility of using virtual reality solutions that can be used as motivating and engaging tools for upper and lower limb physical exercise, respectively. Consequently, two main objectives are established:

O1: It is aimed to design, develop, and test a low-cost wireless standalone platform for VR-based cycling exercises using an IMU paired with the Oculus Quest 2 headset and a common stationary bicycle.

O2: It is pursued to design, develop and test six gamified activities of the VR platform and evaluate them by experts specialized in neuromotor disorder and functional rehabilitation and occupational therapy.

The achievement of these two main objectives aligned with the overall purpose of the thesis are structured in the following six secondary goals:

Regarding the VR solution to promote engagement with the cycling activity (O1), the first step is to develop a VR application that is rooted in the pedalling activity. Thus, (1) this VR application must accurately track the pedalling movement of the individual with no limitations on the nature of tracking, no occlusions, and no calibration requirements. Moreover, it must keep low latency for real-time applications tracking. Then, (2) the VR solution for real-time feedback of cycling motion must be technically evaluated in terms of accuracy and reliability. For this technical validation, the VR platform should be tested with healthy participants to assess to which extent the cadence estimation outcomes were accurate and reliable compared to the gold-standard system. Afterwards, (3) the aim is to assess the feasibility of using the cycling VR platform. To this end, two experimental trials with populations of elderly people and patients with LLD are proposed. The elderly people will assess the VR platform’s sense of presence, user experience satisfaction and its safety. While the patients with LLD (with ataxia or hemiparesis) will assess the VR platform’s credibility, expectancy, and intrinsic motivation aspects. Overall, these experimental trials aim to validate the VR tool in terms of usability by both target populations.

For the generation of a VR solution for bimanual functional rehabilitation (O2), the first milestone is (4) to describe the movements involved in an activity and the ranges of motion of each joint. From this information, (5) a virtual reality experience should allow the user to exercise functional movements for ADL. The design of these activities and the 3D environments should meet the requirements defined by the group of experts and the movement analysis guidelines. Consistently, the last secondary goal is (6) to evaluate the VR application in terms of usability and validity. For this reason, a study is carried out with 5 experts to analyze the feasibility of using the application.

2.3. Scope

Aligning the objectives of this thesis with the hypotheses to be tested, several studies have been carried out. All these studies are collected in this thesis, which is structured as a compendium of scientific publications. The current subsection is a detailed description of the content of each publication and its contribution to the thesis project. This overview of how the published studies make up this thesis is also depicted in Figure 6.

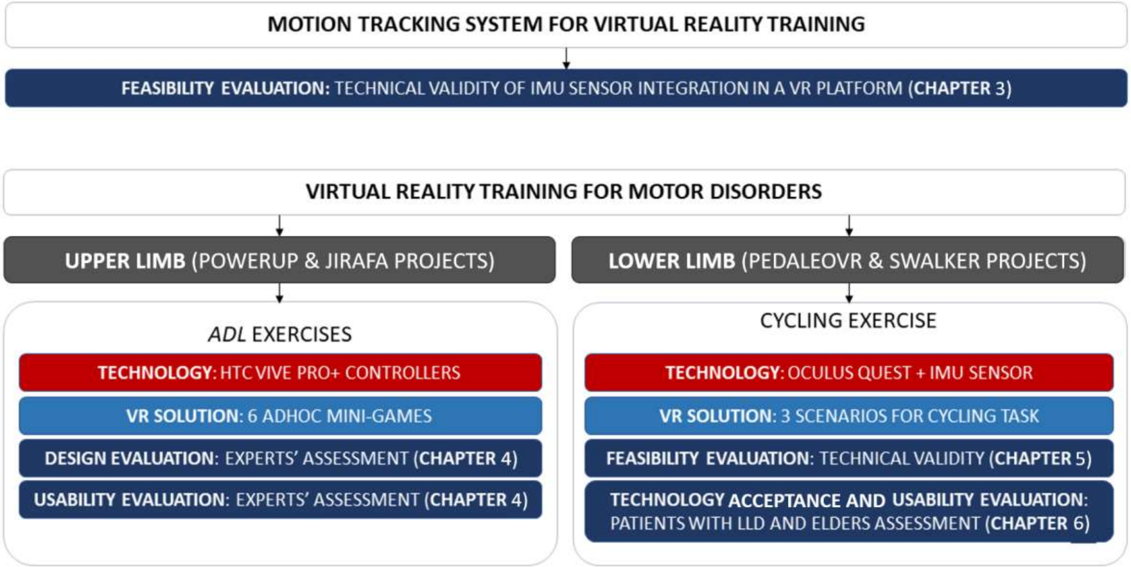

Figure 6. Visual organization of the lines of work of the thesis and the studies of each branch (dark blue box). The training strategy for each limb is shown, as well as the VR hardware and motion tracking/interaction systems employed (red box) and the user experience design of each solution (light blue box).

In the previous **chapter 1** a consistent introduction has been provided to explain the clinical framework of this thesis. In there, we have outlined the reasons and motivation for adopting these solutions as useful tools for exercise interventions for people with motor disabilities caused either by neurological diseases or by suffering the aging process itself.

For accurate motion assessment, we sought to communicate the Werium Solutions inertial sensor called ENLAZA™ with the virtual reality application for Oculus Quest. **Chapter 3** presents this first approach that uses a processing unit that bridges the two devices, so the linked device transmits the captured data via Bluetooth to the Raspberry^{TM} Pi, which sends this information via socket using UDP protocol to the VR application. Initially this application was carried out for the measurement of elbow flexion-extension for the assessment of joint range in the upper limb and its accuracy in the measurement was contrasted against the Oculus tracker itself.

This achievement in the integration of the ENLAZA™ sensor as a motion capture system was later applied to the development of the pedalling platform for the lower limb, since this limb is not usually tracked by external devices and it is necessary to analyse the pedalling motion, as detailed in **chapter 5**. Thus, the next step regarding the upper limb solution is expanded in **chapter 4**, where a solution for remote rehabilitation with the aim of being able to use this system in home-based therapies is presented. Therefore, one of the requirements to enable virtual reality remoting was the use of OpenVR and SteamVR as development frameworks. Consequently, a virtual reality application was designed that could run with SteamVR on devices such as HTC Vive or Oculus Rift and whose interaction mode was based on the manipulation of the controllers. **Chapter 4** presents all the design and technical implementation features that were involved in the creation of each of the 6 functional training games for activities of daily living. It also includes the ranges of joint movement and the movement sequences to be performed in each game. Finally, this chapter also presents the analysis made by experts according to the physical fidelity of the movement of each gamified activity and their suitability for effective rehabilitation of the upper limb.

A new version of the communication methodology between the ENLAZA™ sensor and the VR pedalling platform is presented in **chapter 5**. This improved version of the platform no longer requires the use of the Raspberry™ Pi and now permits direct communication between the ENLAZA™ sensor and the VR application via Bluetooth. This chapter details the real-time motion analysis algorithm applied for counting pedalling cycles and estimating cadence. This processing makes it possible to regulate the virtual environment and provide visual feedback to motivate and guide the user during his activity. The accuracy of this system is evaluated against the gold standard system using the MOTOmed™ digital ergometer and correlating the repeatability, reliability, and measurement accuracy of both systems.

This study confirms that the virtual platform for pedalling is suitable for use in rehabilitation exercise, following a low or moderate cadence. Therefore, it was necessary to evaluate relevant aspects of the platform to know if its design is satisfactory and usable, and especially if it meets the essential characteristics to promote motivation to the continued practice of exercise, enhances the sense of presence, and if users recognize credibility and usefulness to its use during therapy and its safety. Therefore, **chapter 6** includes two case studies carried out with the platform in a geriatric population thanks to the collaboration of the Grupo Albertia Servicios Sociosanitarios (Madrid, Spain) and in a population of patients with motor disorders in the lower limb at Centro Lescer (Madrid, Spain).

The last chapter is the summary and general discussion of all the work carried out. This chapter highlights the novel contribution of each of the developments in technological terms, recognizing the value in the design and development of both applications with their corresponding requirements. The usability and validity studies carried out in each of the developments are discussed. Finally, the future lines of work and considerations of the two projects that make up this thesis are presented.

CHAPTER 3: ACCURACY STUDY OF THE OCULUS TOUCH V2 VERSUS INERTIAL SENSOR FOR A SINGLE-AXIS ROTATION SIMULATING THE ELBOW'S RANGE OF MOTION

Virtual Reality
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ORIGINAL ARTICLE

Accuracy study of the Oculus Touch v2 versus inertial sensor for a single-axis rotation simulating the elbow's range of motion

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Abstract

Virtual reality (VR) has emerged as a valid addition to conventional therapy in rehabilitation and sports medicine. This has enabled the development of novel and affordable rehabilitation strategies. However, before VR devices can be used in these situations, they must accurately capture the range of motion of the body-segment where they are mounted. This study aims to state the accuracy of the Oculus Touch v2 controller when used to measure the elbow's motion in the sagittal plane. The controller is benchmarked against an inertial sensor (ENLAZA^{TM}), which has already been validated as a reliable measurement device. We have developed a virtual environment that matches both the Oculus Touch v2 and the inertial sensor orientations using a digital goniometer. We have also collected the orientation measurements given by each system for a set of 17 static angles that cover the full range of normal elbow flexion and hyperextension motion, in 10° intervals from – 10° (hyperextension) to 150° (flexion). We have applied the intra-rater reliability test to assess the level of agreement between the measurements of these devices, obtaining a value of 0.999, with a 95% confidence interval ranged from 0.996 to 1.000. By analyzing the angle measurement outcomes, we have found that the accuracy degrades at flexion values between 70° and 110°, peaking at 90°. The accuracy of Oculus Touch v2 when used to capture the elbow's flexion motion is good enough for the development of VR rehabilitation applications based on it. However, the flaws in the accuracy that have been revealed in this experimental study must be considered when designing such applications.

Keywords Accuracy · Elbow · Inertial measurement unit · Range of motion · Rehabilitation · Virtual reality

1 Introduction

Recent technological developments can be applied to sports medicine and rehabilitation, helping with both patient assessment and the execution of rehabilitation programs. Wearable sensors are especially popular because they can be used by a wide range of people, from patients with mobility problems to athletes who are recovering from an injury. One of their more important features is the ability to take range of motion (ROM) measurements of body-joints as accurately as goniometers, which are currently the most popular instrument in rehabilitation clinics (Costa et al. 2020). These quantitative measurements of human movement can be used to assess the presence of a motor disorder. In addition, wearable devices can be employed in a free-living environment, expanding their use cases in rehabilitation (Porciuncula et al. 2018). Finally, they also provide an opportunity for the collection of large amounts of data from many patients, which allows the growth of personalized and precision medicine (Dhawan 2016). Many wearable sensors use inertial

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measurement units (IMUs), which contain a gyroscope, an accelerometer and a magnetometer. IMUs are small enough for the devices that employ to provide systematic, objective and reliable monitoring of human movement without hindering it or imposing space limitations (Camomilla et al. 2018).

Another emerging technology that can be used for rehabilitation purposes is immersive virtual reality (VR), usually through headsets that can be combined with other devices, such as omni-directional treadmills, special gloves (Jerald 2019) or controllers. VR's ability to generate realistic images, sounds and other sensations, and, through them, replicate a real environment or create an imaginary world, has proven to be very useful in this field. VR is currently gaining traction in many areas, such as teaching or health, and it is expected to grow even more in the near future (Checa and Bustillo 2020). Concerning rehabilitation, VR has emerged as a valid addition to conventional therapy, enriching new and low-cost rehabilitation strategies (Laver et al. 2017).

VR can provide a positive learning experience, while being motivating and engaging (Maillot et al. 2012). This is especially important in rehabilitation, which can be a tough, prolonged and exhausting experience that patients might feel reluctant to proceed with. Any tool that is able to alleviate this problem is, therefore, particularly useful. Another advantage of VR-based therapy is the possibility of adapting the tasks to each particular patient's needs. Virtual environments can be easily customized, so tasks tailored to the patient's cognitive and physical impairments can be designed, maximizing brain reorganization and reactivating the areas of the brain involved in motor planning, learning and execution (Kim et al. 2005; Boyd and Winstein 2001), while maintaining engagement (Maillot et al. 2012). These modifications would be considerably more difficult and expensive to achieve with real environments.

There are few published studies that use immersive VR for rehabilitation therapies, with most of which are non-immersive experiences in which the patient can see their own body on a standard computer screen (Costa et al. 2020; Cui et al. 2019; Shum et al. 2019; Jost et al. 2021; Postolache et al. 2019; Oña et al. 2018; Borresen et al. 2019; Lee 2017). However, there are some that could be considered immersive VR, such as CAREN (Computer Assisted Rehabilitation Environment), which is a CAVE-like (Cruz-Neira et al. 1992) solution designed for balance assessment and therapy, gait analysis, adaptability, and motor control, among others (CAREN 2021). This integrates an instrumented dual-belt treadmill with a six DOF (Degrees of freedom) motion base and a 3D motion capture system inside an immersive environment. Some studies (De Luca et al. 2020; Rachitskaya et al. 2020; Calabrò et al. 2020; Kalron et al. 2016) have pointed out that this device may be a useful tool in rehabilitation therapies, which encourages the idea that VR could be a useful addition to the therapist's toolset.

1.1 Use of IMUs in immersive applications

Several studies have successfully employed IMUs with immersive applications to measure shoulder joint (Cui et al. 2019) or upper arm and forearm mobility (Kim et al. 2013). These approaches have shown their potential to reduce the human resources and time required to assess the patient's joint mobility in comparison with traditional methods. In addition, these solutions could lead to the development of personalized training methods for upper extremity rehabilitation. There are similar systems that integrate more inertial sensors for motion capture of all body segments (Brandão et al. 2020; Fitzgerald et al. 2007). These solutions allow the patient to receive real-time visual stimuli from a virtual environment, and they provide the therapist with information about the movements performed during therapy. More complex developments (Patil et al. 2020) have proposed pose-tracking systems for virtual interaction by fusing multiple 3D light sensors and IMUs. However, inertial sensors are used to capture the orientation of each body segment, estimating the position and orientation of every joint of the body. This setup enables a real-time 3D avatar reconstruction. The accuracy of the results of this study shows that this solution is comparable to state-of-the-art pose-tracking systems.

1.2 Position and orientation trackers in virtual reality

Motion tracking technologies can be combined with VR, which extends the innate tracking capabilities of this technology to body parts other than the head. This enables rehabilitation therapies to take advantage of some VR features (e.g., immersion, accurate head tracking), while collecting any additional physiological parameters that might be relevant. The more advanced VR Head-Mounted Displays (HMDs) that are currently available on the consumer market are supported by advanced six DOF tracking and are usually based on embedded infrared systems, as is the case with Oculus Rift$^{\text{TM}}$ (Farahani et al. 2016) or the Lighthouse Stations (Dempsey 2016) and is typically used with HTC Vive$^{\text{TM}}$ and other SteamVR-based headsets. These systems provide a very precise tracking of both position and orientation (Niehorster et al. 2017). The HTC Vive$^{\text{TM}}$ tracking system and the WorldViz$^{\text{TM}}$ Precision Position Tracking System have been compared (Niehorster et al. 2017) in terms of accuracy and latency, concluding that the RMS in orientation was less than 0.0113° for the former and less than 0.0053° for the latter for all the rotations. An accuracy analysis of the position and orientation of the HTC Vive^{TM} controllers and trackers (Spitzley and Karduna 2019) has concluded that the mean angular errors for both devices were less than 0.4°. In the same domain of tracking technologies for VR is the Antilatency^{TM} system, which is a positional tracker designed to be used with a VR headset. This uses several trackers consisting of IMU sensors with real-time position correction based on optical data that allows for full-body tracking (LLC 2021). However, despite its potentially high performance, no scientific studies have been found that use this system in the field of motion tracking for rehabilitation.

Despite the positive outcomes in position and orientation tracking of these systems, they still have to deal with two main problems: first, the reduced tracking areas limit the person's movement space and activities; and second, the loss of tracking or changes in height measurements along the tracking space can cause incorrect measurements of the orientation of the device (Niehorster et al. 2017). There are several alternatives to this setup. For example, inside-out tracking uses infrared cameras that are mounted on the headset itself to scan the environment, but they are less accurate and are highly dependent on the environmental conditions (Passos and Jung 2020). Although most motion capture accuracy studies using trackers are not performed with inside-out tracking HMDs (Farahani et al. 2016; Dempsey 2016; Niehorster et al. 2017; Spitzley and Karduna 2019), two studies have focused on the positional and rotational accuracy of the Oculus Touch v1 controller. One of these studies (Jost et al. 2021) acquired static data samples from the device at different step sizes and at different points on a 2.4 × 2.4 m play-place. The authors determined that the maximum positional accuracy error of the Oculus Touch was 3.5 ± 2.5 mm at the largest step size of 500 mm along the z-axis. The other study (Shum et al. 2019) evaluated the rotations in three orthogonal axes for rotation intervals of 90°. The authors found that the rotational accuracy of the system was 0.34° ± 0.38° for the HMD and 1.13° ± 1.23° for the controller. However, no study has examined the orientation accuracy for movements in the sagittal plane. In addition, thorough studies of the accuracy of every component of a VR system that tracks a part of the user's body or an object that the user interacts with are (as have been stated in this section) still lacking. This is an important gap in our understanding of the development of VR-based rehabilitation solutions.

1.3 Aim

The main objective of this work is to validate the accuracy of the Oculus Touch v2 device (Oculus Quest 2 controller) to measure the elbow's motion in the sagittal plane. To achieve this, we used a wireless motion capture wearable device as benchmark. This is based on an inertial measurement unit (IMU) sensor—the ENLAZA^{TM} device—which is already validated as a reliable measuring device for the elbow's range of motion (ROM) (Costa et al. 2020). The previous validity and feasibility study of the use of an inertial sensor to measure elbow and wrist active ROM were a comparative test-retest study between this device and a standard goniometry system with 29 participants. The results revealed that the ROM measurements that were obtained for the elbow had similar values for both systems. The inertial sensor had better reliability when compared to the goniometer for elbow measurements. The intra-rater and inter-rater reliability ICC values ranged from 0.83 to 0.96 and from 0.94 to 0.97, respectively.

However, to be able to do this research, we must first fulfill the secondary objective of this work: to test the capability of an IMU sensor as a VR tracker in conjunction with a VR headset. This will enable us to confidently use the aforementioned IMU sensor as a proper benchmark for the Oculus Touch v2. In immersive applications, VR trackers should fulfill strict accuracy and latency requirements to induce the user's perception of ownership over a virtual body (Banakou et al. 2013). Concerning latency, the existing literature has pointed out that a high delay between the time that a physical movement is performed and an output image is rendered on the HMD can decrease the user's sense of immersion (Farahani et al. 2016). In fact, in VR, an end-to-end latency higher than 30 ms will break the sense of agency and body ownership (Raaen and Kjellmo 2015). Consequently, we must ensure that the IMU sensor respects this limit.

To achieve both aims, we have developed a VR scenario for the Oculus Quest^{TM} 2 that uses both an Oculus Touch v2 and the IMU sensor to track the elbow flexion–extension movement.

2 Methods

2.1 Approach

We have devised the present setup with the aim of establishing a benchmark to test the orientation accuracy of Oculus Touch v2 controllers for VR applications, focusing on its application to the elbow's ROM. This setup has also been designed to integrate the IMU sensor's measurements, which will enable accuracy measurements of both devices (Oculus Touch v2 and IMU sensor) to be taken and compared.

The wireless motion capture system is composed of three fundamental elements: the inertial sensor, a Raspberry Pi based-computer and an Oculus Quest 2 device. We have implemented the communication between the three blocks, which has resulted in a low latency and accurate position tracking method.

2.2 Materials

2.2.1 Inertial sensors

This approach uses an inertial sensor to capture the flexion–extension movement of the forearm. This device contains an IMU module that integrates a three-axis accelerometer, a three-axis gyroscope and a three-axis compass. The IMU sensor also includes a microcontroller unit (MCU) (8-bit AVR, 8 MHz, 32 KBytes of flash memory) that is in charge of acquiring the IMU data; computing the Direction Cosine Matrix (DCM) using the 3D accelerometer, gyroscope and magnetometer data following a published (Premerlani and Bizard 2009) algorithm; and interfacing with a computer unit via Bluetooth.

2.2.2 Computer unit

The computer unit is a Raspberry Pi™, which is a low-cost and small ARM-based computer that supports WiFi and Bluetooth wireless communications. This computing core handles the reception of data from the IMU sensor via Bluetooth, the calculation of Euler Angles orientation from such data, and the sending of these angles via WiFi to a VR device using UPD (User Datagram Protocol), which is chosen to reduce latency.

2.2.3 Virtual reality device

The Oculus Quest™ 2 VR device is used. This is a VR HMD with six DOF for both the headset itself and two Oculus Touch v2 controllers. The Oculus Touch v2 is a handheld unit that contains a set of infrared LEDs. This allows the handheld unit to be tracked by the cameras that are present in the Oculus Quest™ 2 headset (Constine 2015) and an IMU sensor and determines their own orientation.

2.3 System design

The DCM information from the IMU sensor is transmitted via Bluetooth to the Raspberry Pi, which transform the DCM into the angle data that will be used in the VR application that runs in the Oculus Quest 2. Once transformed, the angle data are transmitted via Wi-Fi using UDP to the VR headset. The application uses this data to move a virtual arm that replicates the user's real arm in VR (see Fig. 1). This

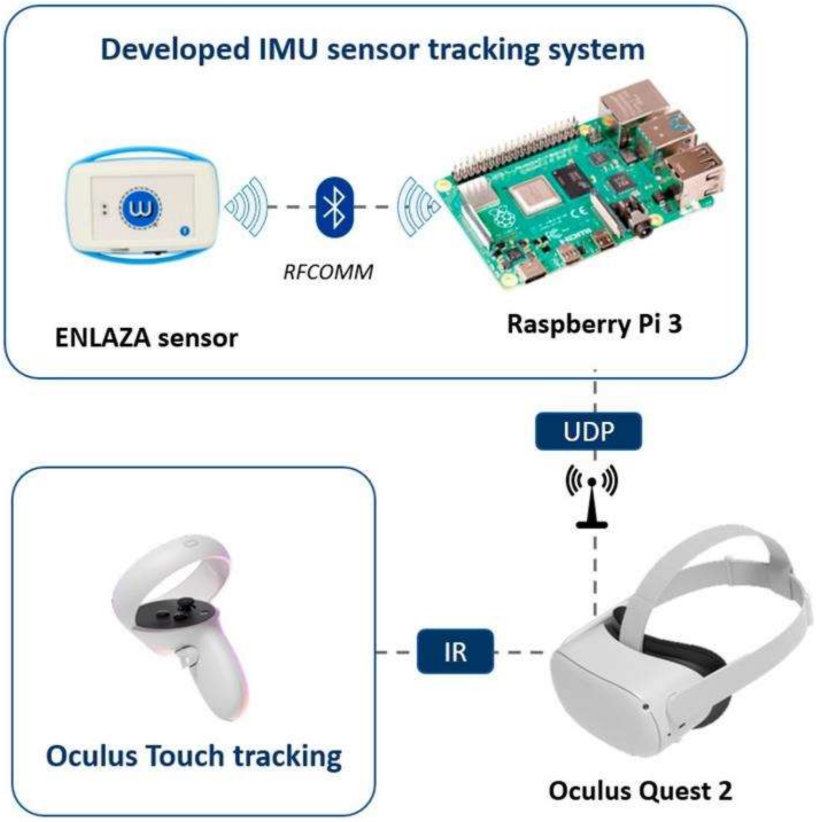

Fig. 1 Diagram of the setup of both orientation tracking systems

movement will also be registered by the Oculus Touch v2. A digital goniometer will be used for the static orientation of the devices.

Bluetooth communication between the sensor and the Raspberry Pi is established using the Serial Port Profile (SPP). This enables the angular orientation data to be sent in a binary format.

The WiFi communication between the Raspberry Pi and the Oculus Quest$^{\mathrm{TM}}$ 2 is implemented using the UDP protocol with a static IP-port endpoint to which data will be sent. We used UDP communication to prioritize low-latency over reliability because the system is tolerant to the loss of some datagrams (Rind et al. 2006).

2.4 Data processing

From the first DCM received, we calculate a calibration matrix to have a new reference frame, which will correspond to the user's initial position. From this neutral position, we can calculate a calibration matrix. Once the calibration matrix is known, we will be able to calculate the transformation matrix for each subsequent DCM received. Next, we can obtain the rotation angle of the reference system, which is equivalent to the rotation measured by the sensor.

This process uses the following calculations: R_{cal} denotes the calibration matrix, R_{s} denotes the data sent by the IMU (in relation to the reference frame), and R_{t} denotes the transformation matrix. We calculate the movement in relation to the calibration using the following equation:

$$R_b = T \times R_a \tag{1}$$

where R_a denotes the initial matrix, representing the initial position and orientation; T denotes the transformation matrix, representing the transformation applied to the initial matrix (a rotation in this case); and R_b denotes the final matrix after the transformation, representing the position and orientation after the transformation. This corresponds in our case to: $R_{\mathrm{s}} = R_{\mathrm{t}} \times R_{\mathrm{cal}}$, so we have that:

$$R_{\mathrm{t}} = R_{\mathrm{s}} \times R_{\mathrm{cal}}^{-1} \tag{2}$$

After calculating R_{t}, we normalize it to ensure that the system is orthonormal.

Finally, we convert R_{t} to Euler angles, using the formulas of the *ZXY* convention, as proposed by the International Society of Biomechanics (ISB) (Wu et al. 2005). The sequence *ZXY* can be intuitively interpreted as the individual Euler rotations. This means that the first Euler angle represents a flexion of the arm, the second represents an abduction of the arm, and the third represents an internal/external rotation of the arm (Campeau-Lecours et al. 2020). These data are sent via UDP to replicate the movement virtually.

2.5 Latency analysis

To measure the total delay of the developed wireless motion capture system, we implemented a time measurement tool in all processes of the data transmission thread. The latency of the system represents the total delay between the instant that the movement occurs to the time that it is displayed on the Oculus Quest$^{\mathrm{TM}}$ 2 HMD. Applying the following approach, we expected to find that the end-to-end latency of this setup stays below 30 ms (Raaen and Kjellmo 2015) to avoid breaking the sense of body ownership in VR experiences.

The simplest way to record these time delays is to write the data packet with a standardized time stamp between events. In this way, when this information is received by the HMD, data time can be stored for later analysis. To support the latency analysis, we store both latency data, as follows: the Raspberry Pi data processing timestamp for each sample and the elapsed-time of the communication process (UDP protocol), which is the time to read an incoming message for 1 min. From these results, the time averages and the standard deviation between the maximum and minimum values are calculated.

Because the inertial sensor has a fixed sampling rate of 50 Hz, this means that we have a data acquisition rate of 20 ms. The times at which each piece of data is received are then captured to know this delay with respect to the sampling rate because a communication rate from IMU to VR HMD of 20 ms would be the expected value in a system with no-latency. This delay reflects the time cost of the three processes: the Bluetooth data transmission between the IMU sensor and the Raspberry Pi, the computation of the Euler angles done by the Raspberry Pi and the UDP socket communication process.

Table 1 shows the time costs of end-to-end communication, the IMU sampling rate and the difference between them. This results in the end-to-end latency. As can be seen, the latency stays inside the values recommended by the literature.

2.6 Data analysis

To analyze the accuracy of the Oculus Touch v2 controller as a tracker and an elbow ROM measurement device, we compare it with the IMU sensor using a digital goniometer

Table 1 Outcomes of the communication rate from the IMU sensor to the VR HMD (ms), IMU sensor sampling rate (ms) and end-to-end communication latency (ms)

Communication rate (ms)	IMU sampling rate (ms)	Latency (ms)
Mean ± SD	Mean ± SD	Mean ± SD
23.709 ± 18.73	20.26 ± 0.48	3.709 ± 18.73

to set the devices in different orientations. The ENLAZA ™, the particular IMU sensor that we used has already been validated for elbow ROM (Costa et al. 2020), will be used the baseline against which the Oculus Touch v2 controller is compared. Accuracy assessment has been established by comparing the means and standard deviations of the pairs of measurements.

To measure the reliability of this validation procedure, we calculated the ICC (95% confidence interval [CI]) using the analysis of reliability of the IBM SPSS Statistics 27 software suite. In this study, the ICC reflects the variation in the measurements made by the devices in the same setup under the same conditions. We took the design of Koo and Li (2016) as a reference and applied the model of two-way mixed effect and absolute agreement definition. We did this because this is an inter-rater reliability study for two different devices and it is expected to observe agreement between their averaged measurements.

2.7 Protocol

We assessed the accuracy of the orientation measures reported by the Oculus Touch v2 at each orientation. Specifically, for accuracy, we looked at whether the roll orientation of the Oculus was stable across space. The orientation of the controllers is referenced with respect to their local coordinate system and not with respect to the external HMD coordinate system. The Oculus Touch v2 bases its measurements on a reference plane that is aligned with its button pad. Therefore, for initial orientation (0, 0, 0), the aim axis is tilted 40° with respect to the horizontal plane of the grip (see Figs. 2 and 3).

To compare static orientation measurements between the Oculus Touch v2 controller and the IMU sensor, both devices were attached to the movable segment of the digital goniometer Silverline™. The Oculus Quest 2 headset was located on a stable table near the goniometer to record the measurement data. The system's setup protocol was run before each data collection session.

The 3D environment built in Unity has two 3D representations of the goniometer (the first for the IMU sensor and the second for the Oculus Touch v2), consisting of two segments and two joints. The first joint enables the rotation of the whole object, and the other joint enables the rotation of the last segment around the *X*-axis, replicating the real goniometer's rotation (see Fig. 4). When the IMU sensor and the Oculus Touch v2 rotate, their angles of rotation are replicated in the corresponding Unity object's joints, to translate the real movement to the VR environment. This allows the data from both devices to be simultaneously stored and represented in the virtual environment.

The angles measured by the IMU sensor and the controller are taken for each set angle that is assessed with the goniometer. This allows us to later evaluate the accuracy of both devices in characterizing this range of angular values. According to the existing literature on the elbow joint normal ROM values (Soucie et al. 2011), healthy men and women aged 9–69 years can achieve a flexion value ranged

Fig. 2 **A** Representation of the local coordinate system of an Oculus Touch v2. **B** Schematic representation of the setup with an Oculus Touch v2 attached to the digital goniometer in its neutral orientation

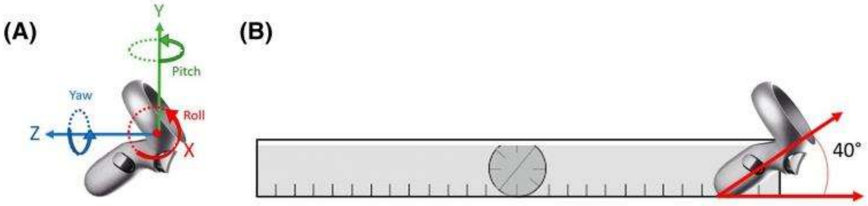

Fig. 3 A controller holder was 3D printed, which allowed the controller to be reliably rotated by 90°. The controller could then perform three orthogonal rotations about a single axis. Both Oculus Touch v2 and the inertial sensor were attached to the digital goniometer

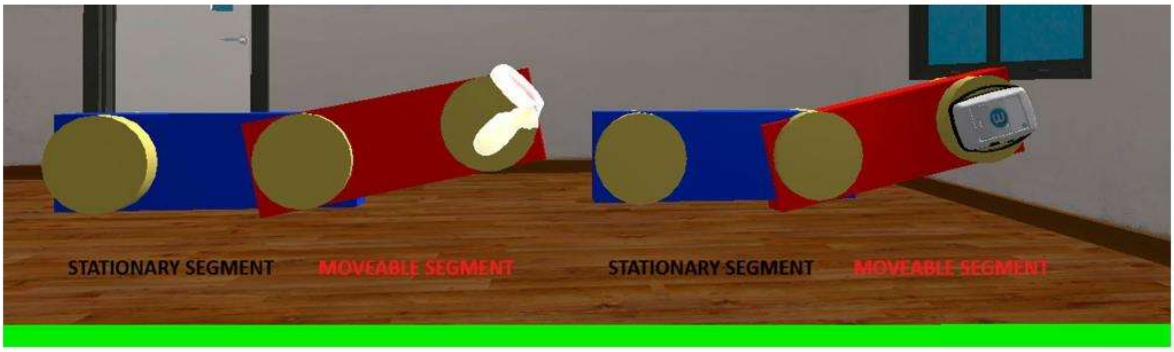

Fig. 4 Virtual goniometers in the Unity 3D engine. The left-hand image represents the angles measured by the Oculus Touch v2 controller, while the right-hand image represents the angles recorded by the IMU sensor

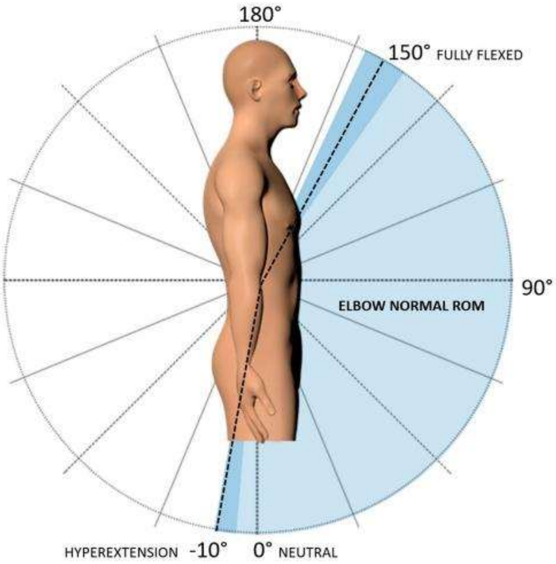

Fig. 5 Representation of the normal range of motion of elbow joint

between 143.5° and 150.0° and a hyperextension value ranged between – 0.8° and – 6.4° (see Fig. 5). Based on these data, we captured the expected normal ROM angles: from 350° (equivalent to – 10° in hyperextension) to 150°, in 10° intervals, which are shown in the results section (Table 2).

3 Results

Table 3 shows the results for the angle measurements performed with the IMU sensor and the Oculus Touch v2, respectively, with both devices fixed to the goniometer. To better characterize the measured angle, the average value of three repetitions for each angle was used instead.

The difference between the mean value of each device and the reference value (goniometer) is shown. This shows the precision achieved by each system. By observing the descriptive results of the measurements, it can be assumed that the average value replicates the reference value because of the narrow dispersion of the samples (standard deviation) for each angle. The standard deviation outcomes of the IMU sensor ranged from 0.127° to 3.307°, and the Oculus Touch v2 standard deviation outcomes ranged from 0.342° to 1.472°.

The standard error of the mean (SEM) was calculated to measure the dispersion of sample means around the population mean. The average standard error of the IMU sensor outcomes is 0.307°, with a minimum value of 0.076° and a maximum value of 1.909°. Meanwhile, the average standard error of the Oculus Touch v2 outcomes is 0.449°, with a minimum value of 0.197° and a maximum value of 0.849°. The degree of agreement between the measurements of the devices was statistically estimated by applying the inter-rater reliability test. We obtained an ICC of 0.999, with values ranging from 0.996 to 1.000 for a 95% confidence interval.

To better illustrate the low dispersion of the results, the mean values and their corresponding standard deviations for each device are graphed in Figs. 6 and 7. The data for 350° have been excluded to preserve the scale of the graph (Fig. 6), but their values are similar to those depicted.

4 Discussion

The present study aimed to compare the static rotation measurements between an Oculus Touch v2 controller and the IMU sensor. These measurements were meant to state the former's accuracy in measuring orientation for the sagittal plane roll rotation, with the aim of tracking kinematic data for an immersive VR application.

Table 2 Results for angle measurements and SEM of 350° to 150° from the IMU sensor

Reference	IMU Mean ± SD	Ref.-IMU difference	SEM
350.00°	+ 350.036° ± 0.747°	+ 0.036°	0.431°
0.00°	− 0.190° ± 0.537°	− 0.190°	0.310°
10.00°	+ 9.553° ± 0.263°	− 0.446°	0.152°
20.00°	+ 19.980° ± 0.127°	− 0.020°	0.073°
30.00°	+ 30.143° ± 0.200°	+ 0.143°	0.116°
40.00°	+ 40.470° ± 0.243°	+ 0.470°	0.254°
50.00°	+ 50.293° ± 0.331°	+ 0.293°	0.191°
60.00°	+ 60.016° ± 0.132°	+ 0.016°	0.076°
70.00°	+ 70.167° ± 0.348°	+ 0.166°	0.201°
80.00°	+ 80.953° ± 0.675°	+ 0.953°	0.390°
90.00°	+ 90.246° ± 0.244°	+ 0.246°	0.1412°
100.00°	+ 99.996° ± 0.295°	− 0.003°	0.170°
110.00°	+ 112.323° ± 3.307°	+ 2.323°	1.909°
120.00°	+ 120.930° ± 0.201°	+ 0.930°	0.116°
130.00°	+ 130.146° ± 0.331°	+ 0.146°	0.191°
140.00°	+ 139.876° ± 0.331°	− 0.123°	0.191°
150.00°	+ 149.923° ± 0.526°	− 0.076°	0.304°
Overall averages	+ 0.286°	+ 2.221°	0.307°

Table 3 Results for angle measurements and SEM of 350° to 150° from the Oculus Touch v2

Reference	Oculus Mean ± SD	Ref.-Oculus difference	SEM
350.00°	+ 350.036°	+ 350.166° ± 0.694°	0.401°
0.00°	− 0.190°	+ 0.566° ± 0.865°	0.499°
10.00°	+ 9.553°	+ 9.070° ± 0.766°	0.442°
20.00°	+ 19.980°	+ 19.273° ± 0.383°	0.221°
30.00°	+ 30.143°	+ 28.456° ± 0.436°	0.252°
40.00°	+ 40.470°	+ 38.473° ± 0.507°	0.293°
50.00°	+ 50.293°	+ 46.746° ± 1.179°	0.681°
60.00°	+ 60.016°	+ 55.893° ± 0.925°	0.534°
70.00°	+ 70.167°	+ 63.680° ± 0.956°	0.552°
80.00°	+ 80.953°	+ 69.716° ± 0.342°	0.197°
90.00°	+ 90.246°	+ 73.003° ± 0.521°	0.301°
100.00°	+ 99.996°	+ 107.943° ± 0.723°	0.418°
110.00°	+ 112.323°	+ 114.733° ± 0.957°	0.553°
120.00°	+ 120.930°	+ 121.823° ± 1.472°	0.850°
130.00°	+ 130.146°	+ 128.863° ± 0.932°	0.538°
140.00°	+ 139.876°	+ 137.366° ± 0.711°	0.410°
150.00°	+ 149.923°	+ 146.46° ± 0.868°	0.501°
Overall averages	+ 0.286°	+ 2.221°	0.449°

An ICC value of 0.999 was obtained for the reliability measurement (Table 4), with a 95% CI that ranged from 0.996 to 1.000, indicating good reliability according to the existing literature (Koo and Li 2016). In addition, the F-test (with truth value equals 0) value that we obtained is 872.322 with a statistical significance of $p \leq 0.001$. Basing on the ICC results, we proceed to discuss the results of each device in more detail for each angle range. For the IMU sensor outcomes, the standard deviation results for each measured angle show low dispersion. However, for the Oculus Touch v2 outcomes, higher standard deviation values are observed in most cases. The angles reported by the Oculus Touch v2 between the static angles of 70° and 110° deviate considerably from the goniometer reference values, as shown in the mean difference between goniometer and Oculus Touch v2 values in Table 2. The average SEM value of the IMU sensor was 0.307°. In contrast, the Oculus Touch v2 showed an average SEM value of 0.449° and a mean difference of 2.22°. The latter result is similar to the mean difference angle value of 1.13 ± 1.23 that was reported by Jost et al. (2021) in their quantitative analysis of the position and orientation of the Oculus Rift^{TM} controllers, which correspond to the first version of the Oculus Touch. These authors already reflected the consistent error in accuracy of the Oculus Touch (v1) for roll rotation in the *z*-axis. According to Ertzgaard et al. (2016) and Youdas et al. (1991), comparing different (inertial and optical) ROM assessment systems, small systematic errors were detected in all planes of elbow motion, ranging from 1.2° to 1.3°. Meanwhile, Brodie et al. (2008) investigated the accuracy of IMUs from XSens Technologies (set as a gold-standard) and obtained a RMS error of between 0.8 and 1.3. Then, assuming that all sensing systems can have an average systematic measurement error around 1.3° (Costa et al. 2020; Youdas et al. 1991; Brodie et al. 2008), values that are below or close to this threshold over the entire range

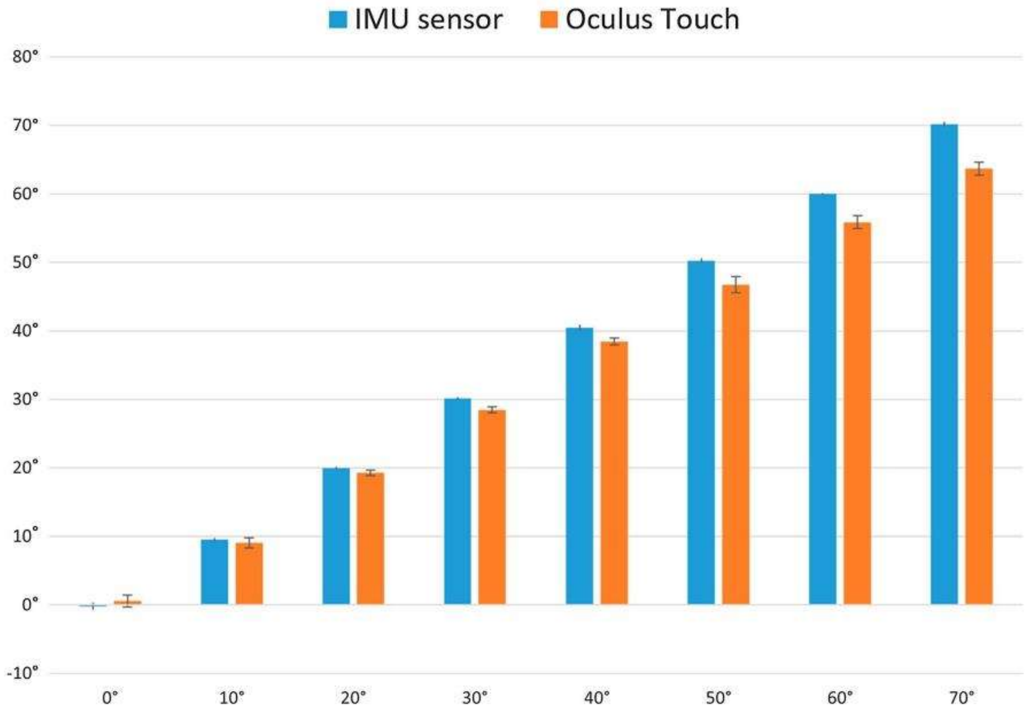

Fig. 6 Comparison of the IMU sensor and the Oculus Touch v2 mean values and standard deviations from 0° to 70°

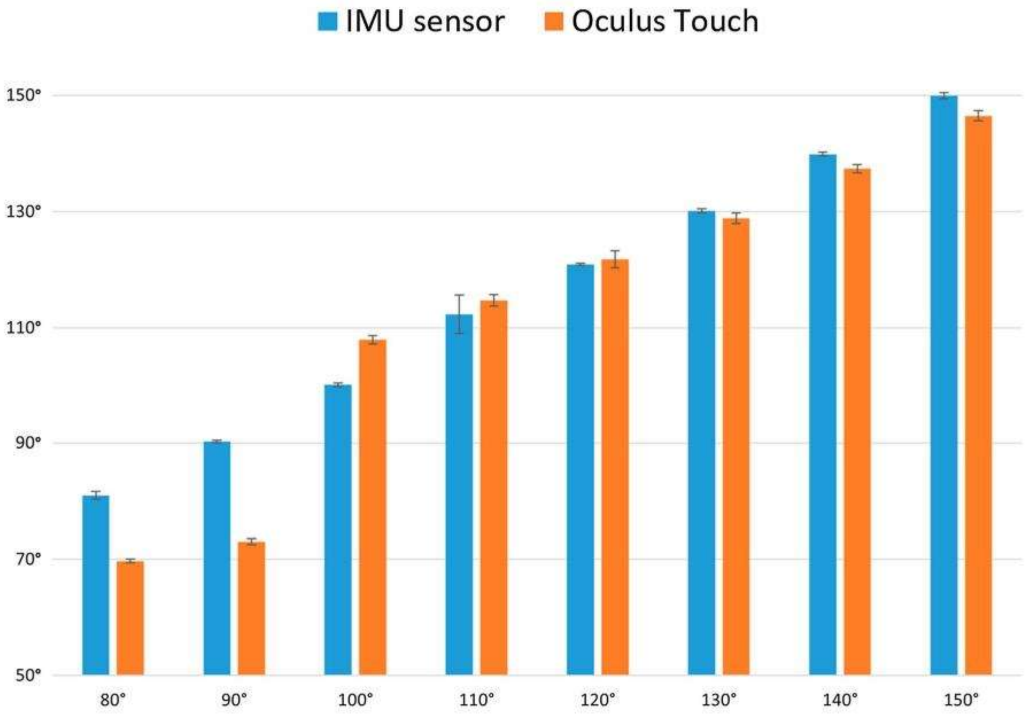

Fig. 7 Comparison of the IMU sensor and the Oculus Touch v2 mean values and standard deviations from 80° to 150°

Table 4 Intraclass correlation coefficient between the average measurements of the IMU sensor and the Oculus Touch v2

	Intraclass	95% Confidence interval		F Test	
	Correlation	Lower Bound	Upper Bound	Value	Sig.
Average measures	0.999	0.996	1.000	872.322	≤ 0.001

of measurement could be considered as acceptable accurate values. In this study, it is evident that the SEM values of the Oculus Touch v2 are not constant over the whole physiological range of motion of the elbow flexo-extension because its accuracy fluctuates seriously in the identified zone from 80 to 110°.

Besides the technical demands on accuracy, it is also essential to consider objective accuracy values from a clinical point of view. However, it is first worth introducing the concept of "minimal detectable change" (MDC) (Fernández Serrano et al. 2014), which is the change in measurement that represents a real improvement in the patient's clinical condition and which, ideally, is not caused by a measurement error. The MDC value is calculated based on the average SEM of the device ($1.96 * \sqrt{2 * \mathrm{SEM}}$). Therefore, in the case of the Oculus Touch v2 (SEM = 0.449°), it should at least guarantee a measurement accuracy of 1.857° to be considered a feasible accuracy device for clinical applications. As shown in Table 3, the controller meets the MDC value at every static-angle in the whole range. In the case of the inertial system (SEM = 0.307°), its MDC value is 1.536°, which is mostly respected throughout the whole range except for the value of 110°.

From these results, it is clear that in the range of angles close to 90°, the Oculus Touch v2 controller loses precision as we approach this particular angle. It is reasonable to speak of the existence of a blind area around the 90° angle, caused either by the hardware sensors or the software that processes their input. This blind area affects the sensitivity of the continuous roll rotation measurement. With that said, it can be considered that the Oculus Touch v2 enables the assessment of the elbow ROM in virtual rehabilitation applications because it accurately captures the extreme (0°, 150°) angle values of the ROM. However, its lack of precision around the 90° angle must be taken into account, so the specific VR application must be designed to properly position the user's arm to avoid having to take accurate measurements around this blind area. Our characterization of the accuracy of the reported 3D orientation of the Oculus Touch v2 in the sagittal plane complements previous studies (Shum et al. 2019), which were focused on the measurement of the positional error of the Oculus Touch v1 controllers. As in the aforementioned study, we conclude that the Oculus Touch v2 controllers could provide a cost-effective alternative for tracking gross upper limb movements in rehabilitation applications.

From all these insights, we can conclude that using higher precision inertial sensors rather than the Oculus Touch would be strongly recommended for VR applications that are designed for elbow ROM rehabilitation. Thus, we recommend the use of devices based on IMUs, such as SlimeVR$^{\mathrm{TM}}$ or DecaMove$^{\mathrm{TM}}$ because they use a technology similar to the one featured in the ENLAZA$^{\mathrm{TM}}$ sensor we used as a benchmark for this study. Regarding more robust motion capture systems, which combine optical and inertial systems, such as Antilatency$^{\mathrm{TM}}$, Tundra Tracker$^{\mathrm{TM}}$ or Indo Track$^{\mathrm{TM}}$, it could be assumed that they would be even more precise. They also enable the capture of more segments, although their potential as full-body trackers for virtual rehabilitation applications should be studied in depth in the future.

We can also conclude that the Oculus Touch v2 tracking data can be used in applications in which elbow movements that cover the full range of motion are performed, especially if most of the time is spent outside the known zone of lowered accuracy. Several movements that are validated for rehabilitation exercises (Shahmoradi et al. 2021) fulfill these criteria, as follows: touching the chin, mouth or opposite shoulder; extending the hand forward to get objects; or holding an object and lifting it or taking it down. These movements require the elbow flexion–extension movement, and their working range mostly avoids the lower accuracy zone of the Oculus Touch v2.

5 Conclusion

The Oculus Touch v2 controllers show a lack of accuracy in some specific orientations of the sagittal rotation plane. Nevertheless, the full ROM of the elbow joint can be properly described in a virtual environment using these devices. The user would only perceive small misalignments in orientation when the controller is close to the 90° angle. In VR applications where a few°s of offset do not matter, the use of Oculus Touch v2 may not be a major problem. However, in applications where high accuracy of orientation measurement is a priority, the use of an IMU sensor is much preferred because the accuracy of the ENLAZA$^{\mathrm{TM}}$, a device that uses this technology, has been confirmed to be very good, if not excellent.

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Availability of data and materials Not applicable.

Declarations

Conflict of interest Raya R. is the CEO of Werium Solutions; Urendes E. is a shareholder of Werium Solutions; Rojo A. is a software developer at Werium Solutions. The other authors declare no conflict of interest. The funding sponsors have no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript and in the decision to publish the result.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Code availability Not applicable.

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CHAPTER 4: FARMDAY: A GAMIFIED VIRTUAL REALITY NEUROREHABILITATION APPLICATION FOR UPPER LIMB BASED ON ACTIVITIES OF DAILY LIVING

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Article

FarmDay: A Gamified Virtual Reality Neurorehabilitation Application for Upper Limb Based on Activities of Daily Living

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Abstract: Patients with upper limb disorders are limited in their activities of daily living and impose an important healthcare burden due to the repetitive rehabilitation they require. A way to reduce this burden is through home-based therapy using virtual reality solutions, since they are readily available, provide immersion, and enable accurate motion tracking, and custom applications can be developed for them. However, there is lack of guidelines for the design of effective VR rehabilitation applications in the literature, particularly for bimanual training. This work introduces a VR telerehabilitation system that uses off-the-shelf hardware, a real-time remote setup, and a bimanual training application that aims to improve upper extremity motor function. It is made of six activities and was evaluated by five physiotherapists specialised in (2) neuromotor disorders and (3) functional rehabilitation and occupational therapy. A descriptive analysis of the results obtained from the System Usability Scale test of the application and a collection of qualitative assessments of each game have been carried out. The application obtained a mean score of 86.25 (±8.96 SD) in the System Usability Scale, and the experts concluded that it accurately reproduces activities of daily living movements except for wrist and finger movements. They also offer a set of design guidelines.

Keywords: activities of daily living; neurorehabilitation; real-time; remote; telerehabilitation; upper limb; bimanual training; virtual reality

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1. Introduction

1.1. Rehabilitation of Upper Limb Disorders

Upper limb disorders (ULD) represent a major concern for healthcare systems because of the considerable economic burden they generate [1]. Most patients with ULD are limited in their activities of daily living (ADL) and require a continuous rehabilitation process [2], whose aim is to restore the lost capabilities and range of motion. Due to the complex nature of this type of injury [3], there are discrepancies about the most effective intervention therapies for ailment. However, most physical intervention methodologies agree that the patient must perform strength and repetition tasks [4–6]. Such tasks enable the patient to work on various parts of the body in a structured and separate manner. However, strength and repetition tasks, by their own nature, do not train the patient in the complications inherent in the organization of whole limb movements. This fact hinders functional improvement in ADL and delays the eventual return of the patient to a productive and fulfilling life.

One of the major concerns involved in this type of rehabilitation is that the patients need to experience enough repetitions to induce the underlying neuroplastic adaptations necessary for their improvement [6]. For many patients, such a volume of therapy is economically unfeasible when it must be done in specialised centers and under the supervision of trained physicians. This is why conventional home-based therapy has become an alternative to extend the practice hours outside the clinic sessions and helps to establish a steady regime. However, most home-based therapy programs are monotonous and repetitive, resulting in a lack of motivation and reduced commitment from the patients [7]. This causes low adherence to treatment, which is crucial for achieving patient recovery. On top of that, such programs also lack the supervision of a therapist that can properly ensure that the exercises are correctly performed. Put together, these two facts are the reason that most home-based programs fail to influence the rehabilitation results in a noticeable way [8].

To try to mitigate this problem, several telerehabilitation solutions have been proposed. However, most are limited to offline monitoring by the therapist, telephone calls, or in some cases, videoconferencing [9–11]. There are more elaborate approaches that involve the installation of equipment in the patient's home [12], designed and custom built specifically for this purpose, and they are therefore, expensive. To avoid this high cost, some authors have tried to use off-the-shelf products, such as video game consoles and peripherals. These solutions, due to their origin in gaming, were expected to increase the patient's engagement. However, they are less than ideal for rehabilitation tasks, since commercial games and their peripherals have not been initially designed for the specific movements that the patient must perform [13,14] and are not yet sufficiently engaging for all patients [13,15]. In some cases, this gap cannot be bridged, due to the inability to develop custom software solutions or modify already available games for proprietary systems, such as game consoles. On top of that, these games are difficult to operate for patients [16].

On the other hand, the use of virtual reality (VR) systems used as complementing tools for rehabilitation and motor retraining have proven successful in promoting patient adherence to therapy and optimising therapeutic gains [17]. Indeed, virtual reality promotes adherence to physical activity (PA), whether commercial or customisable games are used. One study [18] pointed out that the adoption of home-based virtual rehabilitation at home for patients with neuromotor disabilities could be enhanced by using commercial games, but only if these detect compensatory movements, integrate social platforms, provide kinematic reports, and track the patient's progress. However, the development of purpose-built VR games allows one to provide task-oriented exercises, and visual and auditory feedback regarding the performance of the patient's PA [19], which could lead to neuromuscular reeducation and functional improvement [20]. The studies of Wu et al. (2019) [21] and Tarakci, E. et al. (2019) [22] evaluated the effectiveness and feasibility of their VR solutions for hand and upper extremity rehabilitation, respectively, using Leap Motion, a commercial device that enables hand recognition. Their findings pointed out that movements learned in VR environments can be transferred to real-world equivalent tasks in most cases, and that VR engages the player to increase the rehabilitation intensity.

Taking all these facts into account, the benefits that VR telerehabilitation solutions can provide are usually dampened by the use of expensive equipment and/or the need to rely on commercial games. Therefore, it is necessary to build solutions that (a) use off-the-self low-cost hardware VR devices instead of costly and custom equipment, and (b) employ software applications specifically designed for the rehabilitation tasks instead of commercial games.

The main novelty of this work is that it objectively defines the actions and ranges of movement that must be achieved in each VR game for upper limb rehabilitation of bimanual ADL movements. This clarity in the design represents a guideline not found to date in the literature for the construction of virtual environments (VEs) for functional rehabilitation. Additionally, of course, this VR application is supported by a real-time remote system using a novel feasible methodology for video compression.

1.2. Hardware Selection Considerations

Concerning the hardware, most existing game-based therapies focus on two fundamental features: to induce as much immersion as possible and to accurately track the movements of the patient. The former improves the user's engagement in a task that is eminently physical (increases the adherence to treatment), whereas the latter is necessary for assessing if the movements have been properly performed (reduces the need for supervision by a therapist).

To accurately capture the movements of the patient during the rehabilitation session, it is desirable to use sensors with six degrees of freedom (movement and rotation in the three axes). This is why the Kinect™ device is one of the most widely-used systems for motion capture in the field of physiological therapy [23,24].

Virtual reality devices, by their own nature, are capable of very accurate motion capture, since precise tracking of the user's head and hand movements is required for an immersive simulation, which is precisely the other criterion listed before. Therefore, VR provides reliable and precise data about the hands and head motions, and at the same time, produces an immersive simulation. On top of that, unlike other commercial closed solutions, such as video game consoles, it is easy to develop and distribute custom software for most VR devices.

Although VR headsets have their drawbacks (for instance, they may be challenging to use for some stroke survivors and cerebral palsy patients [25]), rehabilitation solutions based on immersive environments are more effective than traditional [26] because they:

- Improve the engagement of the patient: Exergames increase the energy expenditure of the patient and involve both cognitive and physiologicaly rewarding tasks [27], improving the adherence to treatment.
- Provide physical fidelity to real movements: The patient performs motions similar to those needed for analogous daily life situations.
- Provide cognitive fidelity to a real situation: The patient completes activities inside an environment designed to be similar to the real world.

Therefore, it is expected that an immersive VR solution for telerehabilitation will increase the patient's adherence to treatment and improve the fidelity of the movements performed. However, such a solution requires not only the use of a VR head-mounted display (HMD), but also a high-performance computer that renders the virtual experience and sends the movement and session information to the therapist. Such a computer could be a considerable expense—an economic barrier to access that limits this solution.

1.3. Designing Gamified Virtual Reality Content For Rehabilitation

Despite there being currently no standardised criteria for the selection of commercial games for rehabilitation, some literature reviews have succeeded in establishing general guidelines to support the selection of systems [28] and games based on therapist and patient needs [5,18]. These guidelines are designed to evaluate how well existing VR commercial games can be adapted to a rehabilitation scenario; these frameworks focus on characterising the degree to which software and task parameters can be controlled so the therapeutic goals are achieved. As such, they do not aim to guide the design of newly developed VR applications for rehabilitation. However, the aspects they focus on offer valuable lessons that must be taken into account. This is especially important when we consider that clear strategies for the development of home-based rehabilitation therapies based on VR technologies have yet to be determined.

Taking these lessons into account, we can see that VR scenarios must implement motivational strategies based on self-determination and task-oriented challenges [19,29]. Such strategies stimulate the self-improvement of the individual and increase the patient's autonomy [30,31] during the practice. Game mechanics based on them have shown that increasing the user's engagement leads to more practice and also to higher quality practice [18].

Concrete guidelines for the design of effective rehabilitation games that go further than that are still not present in the literature. This lack of guidelines in the design of VR and augmented reality (AR) content has also been pointed out in the field of physical exercise for the older population [32]. Moreover, many rehabilitation solutions present in the literature that use the term "VR" are non-immersive applications in which the user sees a representation of their own body on a computer monitor [26,27,33–35]. This terminology problem is exacerbated when looking for design guidelines for what is now being called "fully-immersive VR" in the literature, since these solutions are not thoroughly explored in the field of functional rehabilitation.

On top of that, the VR-based solutions present in the literature are not focused on bimanual training. This is especially important for this work, since most ADL tasks typically involve asymmetrical bimanual movement [36]. There was an study [37] that focused on bimanual training, but again, not with a VR solution. Game design approaches for bimanual rehabilitation systems in VR are still unexplored, and there is a lack of guidelines that can guide their development.

This work introduces a VR telerehabilitation system that uses off-the-shelf hardware and a newly developed application: FarmDay. This application aims to enhance the bimanual upper extremity motor function of patients with ULD. Its design, due to the aforementioned gap in the literature, was guided by the expert opinions of practicioners and evaluated by them. This way, a set of design principles for the development of VR-based rehabilitation solutions and a collection of valuable lessons learned can begin to form.

2. Material and Methods

The solution developed for this work (named FarmDay) addresses the need to integrate VR exercises with a functional component inside an existing rehabilitation programme, currently performed in a clinic by therapists. It is hoped that these VR exercises will enable a telerehabilitation setup that the patients can use to increase their volumes of work without needing to leave their houses. This rehabilitation programme focuses on patients that have suffered a stroke or other neurological damage.

Various research studies have confirmed that exercises aimed at improving ADL have greater acceptance among adults, increase motivation, and improve adherence to the treatment [38–40]. Therefore, the exercises developed must have an intentional goal that makes the user perform one or more of the functional movements present in ADL.

2.1. VR Real-Time Remote System

As previously stated, one the main drawbacks of a VR solution is the need for an expensive high-performance computer that renders the VE and relays the session's information to the therapist. To avoid this problem, the FarmDay application was designed to run on top of a real-time, remote VR system.

The details of this system are out of the scope of this document, but its architecture can be explained briefly. In this real-time, remote VR system, the VR application runs on a remote high-powered cloud computer (the server), from which the rendered environment is encoded and streamed to a less powerful computer at the patient's home (the client), which in turn is connected to the VR HMD and controllers. This is possible through the use of an elastic down-sampling video compression codec [41]. This architecture relies on the continuous transmission of HMD and controller positions and interaction events from the client to the server. This way, the results of the interactions can be computed on the server and the video image relayed to the client. Figure 1 shows the architecture of this real-time, remote VR system. The FarmDay application is, therefore, run in the cloud server but used by the patient at their home. This way, the cost of running this setup for the user is greatly reduced.

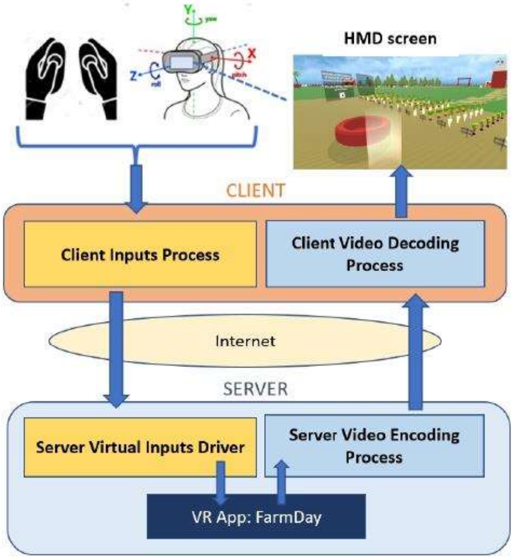

Figure 1. Diagram of the the real-time, remote VR system architecture.

Every VR application designed to use this system must use the OpenVR libraries, since it must use four custom components developed for it:

- A client inputs process that captures the HMD and controllers inputs and sends them to the server.
- A server virtual inputs driver that receives the input data from the client and feeds them to the actual VR application running in the server (in this case, FarmDay).
- A server video encoding driver that captures the rendered VE product of these interactions, encodes it, and sends it to the client.
- A client video decoding process that receives the encoded video, decodes it, and shows it in the client's HMD.

2.2. *VR Application*

The FarmDay application was developed using the Unity3D game engine v.2019.2.13f, mainly using the collection of scripts and predefined elements of the Virtual Reality ToolKit (VRTK) v.3.3.0 framework. This open source toolkit was used to implement the virtual space locomotion, object grasping interactions, object interaction via pointers, 3D button interactions, and 3D body physics within the virtual space.

(i) VR framework and platform

As stated before, and due to the custom real-time remoting system developed in OpenVR, it was consequently determined that the VR application should be built for systems compatible with the OpenVR platform. Then, FarmDay was designed for the OpenVR SDK (Software Development Kit), so the real-time remote system can be used. The VR application was developed entirely as a single Unity scenario. In this 3D scenario, six activities are distributed through specific areas of the environment. For interactive actions and locomotion control, the VRTK prefab module was used. The VR solution generated supports the HTC Vive™ and Oculus Rift™ platforms' controllers, which are used for the interactions.

(ii) Gamification elements

The gamification strategy of the activities included in the FarmDay experience is based on goal achievement. Thus, each activity is composed of a sequence of actions that the user must perform to complete the task. The achievement of these objectives implies that the motions of the different body segments involved in the ADL functional movements were properly performed.

(iii) Design of activities

Of the six activities offered by the application, three are based on real-life situations and were designed following the guidelines and advice of five physiotherapists specialised in neuromotor disorders from the Spinal Cord Injury Foundation (Fundación de Lesionado Medular, FLM) and CEU San Pablo University (Universidad San Pablo CEU, USPCEU). They are hand-washing, pouring a drink, and playing the piano.

The three remaining activities were themed around farm life and designed to involve movements similar to ADL. They are animal caring, picking apples from trees, and picking vegetables up off the ground. This way, the user can perform a bigger variety of exercises, hopefully increasing their adherence, reducing the feeling of boredom, and allowing them to work on similar movements in different ways.

(iv) User Interaction

The FarmDay application begins by placing the user at the entrance of the farm, allowing them to explore the environment by moving around the delimited physical space, either by directly walking or by using a teleport functionality that can be activated with any of the two controllers. Additionally, game selection panels have been distributed throughout the environment. Through them, the user can teleport from one activity to another without having to physically traverse the VE.

These game selection panels consist of six interactive buttons that react when pressed with the controller, moving the user to the zone of the selected activity. The zone for each activity has a floating transparent panel which shows the objective of the activity and contains a play button. When the user presses the play button (by moving their hand), this game panel fades out and the activity starts. Once the activity is completed, the game panel fades in again, allowing the user to repeat the activity as many times as desired, restoring all the environment elements to their initial positions.

Design of Activities

Since each of the six activities aims to make the user perform movements specific to a particular ADL, it was essential to identify such movements. It was also necessary to determine the range of motion (ROM) for each joint (neck, shoulder, elbow, and wrist) and action, to make the tasks' movements as faithful as possible to what the user would do in a real-world ADL. A recent state-of-the art review of devices for performing physical therapy at home or assisting with ADLs identified at least 15 systems that employ VR feedback, and in most of these cases, wrist support (ROM assessment), and in a few cases grip function, was considered [42]. No further information on finger movements is given. Therefore, the definition of the virtual scenarios and the placement of the interactive virtual objects were done in such a way so the user must reach a certain ROM for each joint to actually perform the tasks. All six virtual scenarios are depicted in Figure 2.

By applying inverse kinematics to the controllers' positional and rotational data, the ROMs in the sagittal and horizontal planes of these body joints were evaluated. Tables 1–6 detail the sequence of actions to be performed in each activity, the movements of the upper limb, and the ROMs involved for each joint. Each activity is further described in detail.

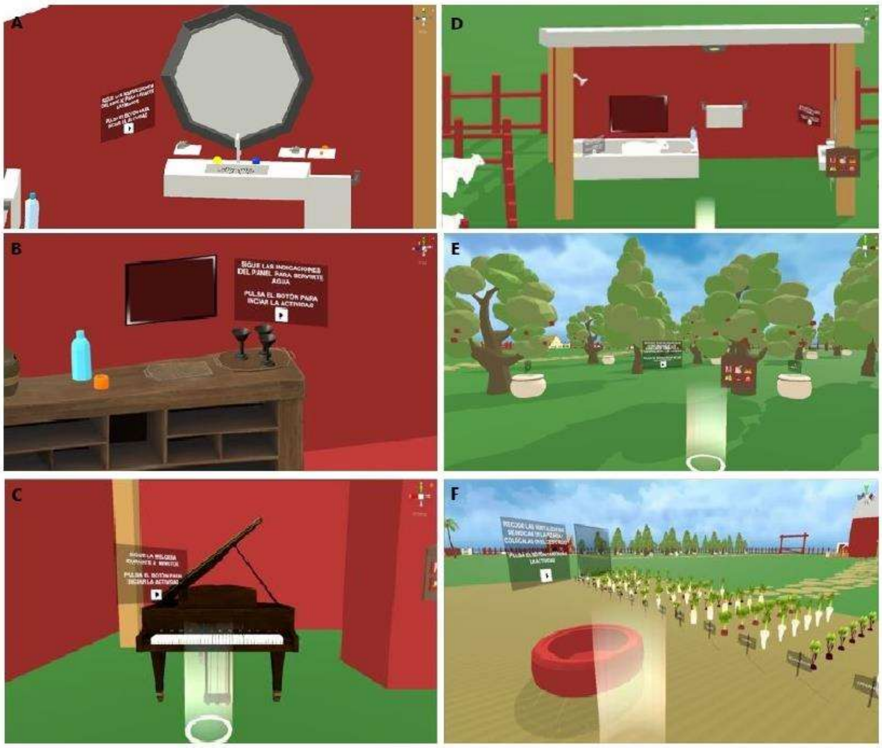

Figure 2. Virtual environments for the activities. (**A**) The cabin area for the hand-washing activity, consisting of a faucet, a mirror, and the interactive objects: gloves and soap. (**B**) The barn dinning area for the pouring a drink activity. (**C**) The interactive keyboard for the playing the piano activity. (**D**) The toilet cabin area for the animal caring activity. (**E**) The forest area for the picking apples from trees activity. (**F**) The orchard field area for the picking vegetables up off the ground activity.

Table 1. Sequence of actions and the upper limb movements involved in the hand-washing activity.

Action	Upper Limb Movement	Target ROM
Turn on/off the faucet	Shoulder flexion	90°
	Elbow extension	0°
	Elbow pronation	70°
	Wrist flexion	45°
Placing hands under water	Shoulder flexion	45°
	Elbow flexion	90°
	Elbow neutral position	0°
	Wrist neutral position	0°
Soap hands	elbow flexion	45°
	Wrist radial-ulnar rotation	15°

Hand-washing activity: In this task, the user must follow the instructions shown in the mirror, step by step, to complete the action of washing their hands. The user is located in front of the toilet cabin and must move to stand in front of the sink, whose tap can be opened and closed by interacting with the yellow and blue buttons. Small shelves are placed to the left and right of the tap. On top of those shelves there are objects that must be reached: gloves and soap (see Figure 2A). The height and distance of these shelves and the buttons on the faucet are configured according to user's position to ensure the proper shoulder extension, elbow movements, and wrist rotations (see Table 1).

Table 2. Sequence of actions and the upper limb movements involved in the pouring a drink activity.

Action	Upper Limb Movement	Target ROM
Grab a bottle/glass	Shoulder flexion	45°
	Elbow flexion	90°
	Elbow neutral position	0°
	Wrist flexion	45°
Pour the liquid into the glass	Shoulder flexion	45°
	Shoulder internal rotation	45°
	Elbow pronation	35°
	Wrist neutral	0°
Take the glass to mouth	Neck extension	10 °
	Shoulder flexion	65°
	Elbow flexion	130°
	Wrist radial deviation	20°

Pouring a drink activity: In this task, the user must follow the instructions shown on the board, step by step, to complete the actions of pouring water into a glass and drinking from it. Initially, the user is placed in front of the bar where the interactive objects (bottle, glass and wooden board) are placed (see Figure 2B). They are arranged at a comfortable height and a distance appropriate to perform the flexion movements at the elbow, shoulder, and wrist to reach the objects; and elbow pronation and wrist movements to grab the objects (see Table 2).

Table 3. Sequence of actions and the upper limb movements involved in the playing piano activity.

Action	Upper Limb Movement	Target ROM
Pressing the piano keys	Shoulder flexion	30°
	Elbow flexion	70°
	Elbow pronation	70°
	Wrist flexion	45°

Playing the piano activity: In this task, the user stands in front of the piano keyboard. The height of the piano is set to allow the subject to perform the elbow, shoulder, and slight wrist flexing movements (see Figure 2C). To complete the activity, the user must follow the melody for 2 min. This involves pressing the keys shown on the score panel (see Table 3).

Animal caring activity: In this task, the user must follow the instructions on the board, step by step, to complete the action of showering a sheep. Initially, the user is located in front of the bathtub (see Figure 2D). The interactive objects (buttons to activate the bathtub tap, soap bottle, and brush) are placed on the shelf of the shower or the floor, allowing the movements of flexion of the shoulder, the elbow, and the wrist, and internal rotation of the shoulder and elbow pronation to pour the soap on the sheep. Additionally, the brushing action induces elbow abduction (ABD) and adduction (ADD) movements and wrist radial-ulnar rotation movements (see Table 4).

Table 4. Sequence of actions and the upper limb movements involved in the animal caring activity.

Action	Upper Limb Movement	Target ROM
Turn on/off the faucet	Shoulder flexion	30°
	Elbow extension	0°
	Elbow pronation	70°
	Wrist flexion	45°
Pour soap	Shoulder flexion	45°
	Shoulder internal rotation	45°
	Elbow flexion	0°
	Elbow pronation	35°
	Wrist neutral	0°
Brushing the animal	Shoulder flexion	30°
	Shoulder ABD	45°
	Shoulder ADB	45°
	Elbow flexion	30°
	Elbow pronation	70°
	Wrist extension	20°
	Wrist radial deviation	15°
	Wrist ulnar deviation	20°

Table 5. Sequence of actions and the upper limb movements involved in the picking apples from trees activity.

Action	Upper Limb Movement	Target ROM
Grab apples	Shoulder flexion	100°
	Shoulder ABD/ADD	20°–30°
	Elbow flexion	0°–30°
	Wrist extension	20 °
	Neck extension	20 °
Put apples into the basket	Shoulder flexion	30°
	Shoulder ABD/ADD	20°–30°
	Elbow neutral position	0°
	Wrist flexion	45°
	Neck flexion	10°

Picking apples from trees activity: This task asks the user to pick as many apples from the trees as possible in 2 min and place them in the baskets next to each tree (see Figure 2E). To do this, the user must move to each tree. The collection of the apples from the tree and the placement of these in the baskets involves movements of flexion and extension of the elbow, shoulder, and wrist. Additionally, this action induces shoulder ABD/ADD movements. On top of that, the task forces the user incline their neck tilt, for gaze redirection (see Table 5).

Table 6. Sequence of actions and the upper limb movements involved in the picking vegetables up off the ground activity.

Action	Upper Limb Movement	ROM
Grab vegetable	Shoulder flexion	0°–30°
	Elbow neutral position	0°
	Wrist flexion	10°
	Wrist ulnar deviation	15°
	Neck flexion	10 °
Put vegetables into the basket	Shoulder flexion	30°
	Shoulder adduction	20°
	Elbow neutral position	0°
	Wrist flexion	10°
	Wrist ulnar deviation	15°
	Neck flexion	10°

Picking vegetables up off the ground activity: This task asks the user to collect the vegetables indicated on the board and place them in a red basket. Once the correct vegetable is picked and placed, the new vegetable to be picked is shown on the board. There is no time limit for the picking action for each vegetable, so this activity lasts as long as the user needs to pick all the vegetables listed. This list varies randomly (5 to 10 elements) each time the task is started. Thus, the user will have to move to a particular row of vegetables inside a zone defined prior to the start of the VR application. The reach to the vegetables on the ground and the placement of these in the red basket induce elbow and shoulder extension movements, wrist flexion, and raldial-ulnar deviation movements to grab the objects, along with the flexion of the neck for gaze redirection (see Figure 2F).

2.3. Usability and Design Evaluation

Five experts from FLM and USPCEU were asked to test the VR application. These experts were all physiotherapists specialised in neuromotor disorders. For these tests, a SteamVR room was set up to delimit a 3×2 m^2 free movement physical area. The HTC Vive™ HMD and controllers were used. Before starting, they were instructed on how to use the controllers to teleport, grab objects, and interact with them. Then, they were asked to perform all six activities of FarmDay in an order of their choosing.

To evaluate the ability of the activities to achieve rehabilitation for specific actions, a customised, open-ended, non-scaled qualitative response survey was developed based on human–computer interface acceptability standards [43]. After performing their test, for each activity, the experts were asked "Does the activity allow for the movements required for the rehabilitation of this action? If the answer is negative, please indicate the aspects that need to be improved." This way, in the case of a negative answer, the expert was asked whether the movement/interaction could be performed in another way and which modifications could be made to improve the activity.

To evaluate the ease of use of the VR experience, a Standard Usability Scale (SUS) questionnaire was also included [44,45].

3. Results

Tables 7 and 8 show the experts' answers to the qualitative response survey's questions. In those cases in which the experts confirmed that the activity permitted the performance of the functional ROMs identified for each action, the answer was "The activity is adequate".

Table 7. Results of activities' evaluation by FLM experts.

Activity	Answer FLM1	Answer FLM2
Hand-washing	No. Grabbing the gloves is an uncomfortable movement. It could be better if the gloves were already attached to the controllers.	No. Grabbing the gloves is an uncomfortable movement. It could be better if the gloves were already attached to the controllers.
Pouring a drink	No. The action "take the glass to your mouth" does not consider the wrist rotation.	No. Grasping actions do not involve finger movements.
Playing the piano	No. Key-pressing action does not involve finger movements. Drums will be a better alternative.	No. Key-pressing action does not involve finger movements.
Animal caring	Yes. The activity is adequate.	Yes. The activity is adequate.
Picking apples	Yes. The activity is adequate.	Yes. The activity is adequate.
Picking vegetables	Yes. The activity is adequate.	Yes. The activity is adequate.

Table 8. Results of activities' evaluation by USPCEU experts.

Activity	Answer USPCEU1	Answer USPCEU2	Answer USPCEU3
Hand-washing	No. Grabbing the gloves is an uncomfortable movement. It could be better if the gloves were already attached to the controllers.	Yes. Grasping actions do not involve finger movements.	No. Grabbing the gloves is an uncomfortable movement. It could be better if the gloves were already attached to the controllers.
Pouring a drink	Yes. The activity is adequate.	Yes. However, grasping actions do not involve finger movements.	No. Grasping actions do not involve finger movements.
Playing the piano	No. Key-pressing action does not involve finger movements. 3 keys pressing allows one to evaluate precision.	No. Key-pressing action does not involve finger movements.	No. Key-pressing action does not involve finger movements.
Animal caring	Yes. The activity is adequate.	Yes. The activity is adequate.	Yes. The activity is adequate and it also promotes shoulder ABD/ADD movements.
Picking apples	Yes. The activity is adequate.	Yes. The activity is adequate and it also promotes raising the arms above the head.	Yes. The activity is adequate.
Picking vegetables	Yes. The activity is adequate.	Yes. The activity is adequate and it also integrates crouching exercise.	Yes. The activity is adequate.

To interpret the SUS score, it must be converted to a percentile rank. The outcomes from the experts' evaluations are shown in Table 9. Based on the distribution of all scores, a raw SUS score of 86.25 converts to a percentile rank of 86.25%, which objectively means that the evaluated system has a higher perceived usability than 86.25% of all products tested.

Table 9. Results of the System Usability Scale.

Experts	Score
FLM Expert 1	80.00/100.00
FLM Expert 2	95.00/100.00
USPCEU Expert 1	92.50/100.00
USPCEU Expert 2	95.00/100.00
USPCEU Expert 3	75.00/100.00
Mean (±SD)	86.25/100.00 (±8.96)

4. Discussion

4.1. Game Design Evaluation

As can be seen in Tables 7 and 8, the consulted experts tended to agree on several points. On the positive side, all experts (5/5) concurred that the three activities designed around the farm life theme are adequate for the corresponding ADL movements. As explained in Section 2.2, these were not initially proposed by the experts. Instead, they were explicitly designed to involve ADL movements, their representativeness of real-life situations being only a secondary concern. This shows that having the ability to decide on the movements first and then planning an activity around them afterwards helped the designers to achieve higher movement accuracy. Therefore, if possible, this should be the approach followed by designers of future VR scenarios. Moreover, the positive response of the experts precisely to the activities that were not suggested by them showed that they welcome such an approach.

Looking at the answers to the these activities, three of the experts were not concerned that the tasks involve movements in addition to those specifically targeted: USPCEU2 favoured the crouching exercise in the picking vegetables activity, USPCEU3 liked the shoulder ABD/ADD movements in the animal caring activity, and USPCEU2 indicated that the raising of the arms above the head in the picking apples activity is desirable. This shows that the designers of tasks focused on inducing ADL movements should not be concerned about expanding them to also cover other movements.

The three initially proposed activities were not perceived as totally adequate for the real movements: 5/5 experts found one inaccuracy with the playing the piano activity, 4/5 experts with the hand-washing activity, and 3/5 experts with the pouring a drink activity. For these activities, the experts were concerned about certain limitations on the wrist and finger movements, with the former being present in the hand-washing and the pouring a drink activities, and the latter in the pouring a drink and playing the piano activities.

In particular, the hand-washing activity was implemented with the strategy of grabbing a pair of gloves instead of offering a realistic simulation for the hands of the user. This means that the movements of rinsing the hands under the tap induce slightly forced wrist rotations with respect to the natural movements. To solve this problem, it would be ideal to replace the controllers with a hand tracking controlerless setup for this specific exercise.

A similar problem was observed in the simulation of bringing the glass of water to the mouth. Although the hand and controller are assessed as being close to the user's headset, the need to perform the wrist rotation movement involved in tilting the glass to empty the water is not evident. This is mainly attributed to the following facts: First, the application simulates emptying the glass at a horizontal distance of 6 cm from eye level to prevent the user from bumping the controller against their HMD. Second, the grabbing of the glass involves an object snap, so that the position of the object is consistent with the movement. Therefore, the user does not feel the need to rotate the wrist any further.

Concerning the finger movements, the experts specially miss them in the playing the piano activity. This indicates that this activity is not suitable for VR controllers, and as with the hand-washing movement, it would be ideal to replace the controller with a hand tracking setup. Two experts also indicated the inaccuracy of the finger movements in the glass grabbing part of the pouring a drink activity. The VR application expects the user to press the trigger button to grab the glass, since this act induces flexion–extension movements in the index finger, but they considered that this was not suitable enough. However, one expert stated positively that in the playing the piano activity, each musical note was represented by three keys in the keyboard (see Figure 2). This has the potential to allow the physiotherapist to evaluate whether the precision of the movement of tapping a single key was accurate or not without interrupting the task. This design could be exploited from the point of view of motion analysis.

Therefore, it can be seen that the tested setup (HTC Vive™ controllers) is not particularly adequate for wrist and finger movements. According to the expert's opinion, for such tasks, a designer should take into account that a hand tracking setup would be probably better suited. With that said, a study of telerehabilitation using HTC Vive™ devices [37] has shown that the handling of these controllers improved finger extension, so further testing is needed in this regard.

4.2. Bimanual Interaction and Hand Movement

A central principle to the design of the six activities was the bimanual interaction, since this approach provides greater freedom of movement to the user and offers a context particularly faithful to that found in the ADLs. Therefore, this work combines a task-oriented strategy [29] with bimanual coordination. In the future, it would be interesting to explore if this approach offers an improvement in the effectiveness of functional training in comparison to the more commonly used approach of movement restrictions. One study [37] showed significant evidence of improvement in bilateral movements derived from intervention with bimanual interaction, but more studies are needed. This is a gap in the literature that was identified in Section 1.3. However, future work should consider dissociated finger movements using hand tracking and gesture detection systems to enable this improvement. In fact, the integration of systems such as Leap Motion could solve the analysis of finger movements. Although the studies reviewed by Pererira et al. (2020) [19] implemented hand movement tracking, none took advantage of this feature, with the exception of Wu et al.'s [21] work, which used Leap Motion for validation of wrist flexion and extension and radial and ulnar deviation. Therefore, although the current study has not been able to contribute to this aspect, we identify that further work is needed in this area.

4.3. Usability Outcomes

According to the results of the System Usability Scale questionnaire for the application, where the average value was 86.25 (SD = 8.96) and the minimum SUS score obtained was 75.00/100.00, FarmDay was accepted by the experts, and its ease of use can be rated as excellent [45], as shown in Figure 3. From this assessment, it can be inferred that the design of the VE; the distribution of the activities; and the intuitive way of interacting and the gamification strategy in each activity are adequate for this purpose. The design of the experience is focused on being easy to handle and on making it simple for the user to quickly learn the mechanics of each activity. This is relevant, since the existing literature has stated the need to incorporate patient-centred methodologies and ADL-enhancing games in telerehabilitation approaches [35]. Therefore, when designing activities similar to those presented in this work, it is important to focus not only on the generation of ADL-enhancing games themselves [46,47], but also on their ease of use for patients with ULD, an aspect that can be evaluated with the rating provided by the System Usability Scale.

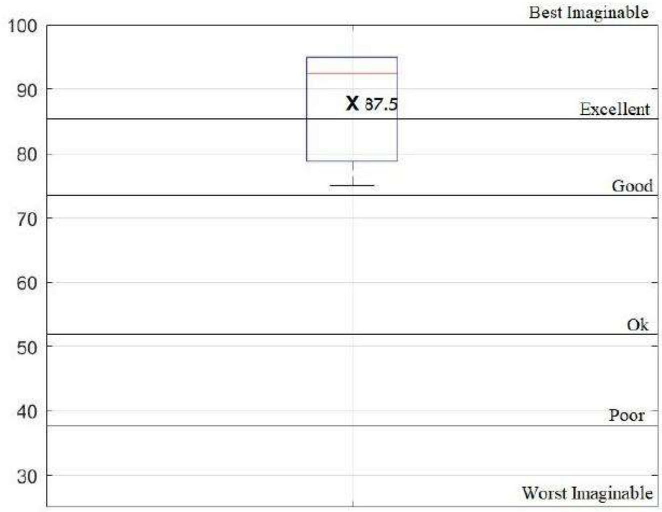

Figure 3. Boxplot of System Usability Scale outcomes, overlapped with the 7-point adjective SUS scale interpretation [45].

4.4. Limitations

Finally, several methodological considerations have to be made. Although the work presented here was a study of the usability and feasibility of the application, only professional input was considered. In this area, clinicians' expertise is considered to be more important than users' perspectives [48], since in the neurorehabilitation field, the physiotherapist has better knowledge about how to implement an effective rehabilitation programme. On top of that, they are involved in the direct delivery of the rehabilitation process. Nevertheless, future studies with patients with ULD are needed to corroborate that the proposed VR application contributes to the physical improvement of the upper extremity and manages to motivate and maintain adherence to the rehabilitation treatment. Such a study could be made possible by the real-time, remote VR setup presented, which reduces the cost of deploying such a solution at the patients' homes. This is aligned with the literature's suggestion [46] to provide feasible solutions for telerehabilitation, allowing the patients to benefit from social care and home-based rehabilitation [35].

5. Conclusions

This work introduced a VR telerehabilitation system that uses off-the-shelf hardware, a real-time remote setup, and a bimanual training application that aims to improve the upper extremity's motor function. It is made of six activities and was evaluated by five physiotherapists. Two of them specialised in neuromotor disorders at Fundación de Lesionado Medular and three of them specialised in functional rehabilitation and occupational therapy at CEU University. The definition of the sequences of actions and the range of movement for each joint and action for all six VR games for bimanual ADL exercises have been established. From the evaluation of this solution, it can be concluded that all six activities could be used for upper limb functional rehabilitation, with the exception of wrist and finger movements. Except for these caveats, the experts agree that the activities enable the user to perform suitable upper limb ADL-exercises in a realistic and immersive context. On top of that, the authors believe that this discussion offers a set of valuable lessons that can be applied to any future design of a VR application for rehabilitation of patients with ULD, particularly for bimanual interaction. Finally, the high usability score of the application reflects the reliability of the virtual reality tool for patients with UDL.

Author Contributions: A.R.: conceptualisation (equal); study implementation; software (lead); formal analysis (lead); writing—original draft (lead). J.Á.S.-P.: writing—review and editing (equal). Á.S.-P.: writing—review and editing (equal). R.R.: writing—review and editing (equal). R.G.-C.: conceptualisation (lead); writing—original draft (supporting); writing—review and editing (lead). All authors were accountable for the final version of the article. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ABD	Abduction
ADD	Adduction
ADL	Activities of Daily Living
FLM	Fundación Lesionado Medular (Spinal Cord Injury Foundation)
HMD	Head-Mounted Display
ROM	Range of motion
SDK	Software Development Toolkit
SUS	System Usability Scale
ULD	Upper Limb Disorders
USPCEU	Universidad San Pablo CEU
VE	Virtual environment
VR	Virtual Reality
VRTK	Virtual Reality ToolKit

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CHAPTER 5: VIRTUAL REALITY APPLICATION FOR REAL TIME PEDALLING CADENCE ESTIMATION BASED ON HIP ROM TRACKING WITH INERTIAL SENSORS: A PILOT STUDY

Virtual Reality
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ORIGINAL ARTICLE

Virtual reality application for real-time pedalling cadence estimation based on hip ROM tracking with inertial sensors: a pilot study

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Abstract
Virtual reality (VR) applications on rehabilitation a home-base exercise experiences have boomed in the last decade. This is mainly because their entertainment capacity creates a sense of immersion in the users, which enhances adherence to their use. In addition, offering body-related visual feedback is a proven approach to the physical training towards a goal. Recent literature showed the exercise of pedalling has the potential to provide a high number of flexion and extension repetitions of the lower limb in reasonable therapeutic time periods to improve muscle activity, strength and balance in elders, but also motor improvements in patients with neurological injuries. The objective of this work is to present a low-cost wireless application in virtual reality (VR) for pedalling exercises. The platform developed consists of a VR headset and an inertial measurement unit (IMU). The VR headset processes the kinematic information of the IMU to estimate the cadence of the pedalling, while the IMU sensor tracks the angle of hip flexion/extension movement of the user. In order to confirm the suitability of this cadence estimation system, our approach is confronted with a cycling platform developed and validated in a previous study. In the present study, we carried out two repeated sessions with 13 subjects at 3 set speeds: slow (30 rpm), medium (60 rpm) and fast (90 rpm). The Spearman's correlation (PC) between both systems for the 3 speeds and sessions shows high correlation values for low and medium speeds and moderate correlation for high speed. The SEM results for each system show low measurement error (about 1 cycle) for both systems at every target speed, except for the virtual cycling platform at the highest speed (SEM of VCP at 90 rpm = 3.24 cycles). The repeatability analysis based on ICC (3, 1) absolute agreement shows consistency in all measurements for both systems at high speed and also reflects the irregularity in measurements at low and medium speeds, where participants were less stable during testing due to entertainment from the VR system. All in all, it is concluded the validity of the cadence estimation system for pedalling exercises with low intensity. This development allows us to control the virtual environment by adapting the visual stimulus to cycling cadence. The proposed system can generate sensitive inputs to influence the user's pedalling cadence.

Keywords Virtual reality · Low-latency · Real-time tracking · Inertial unit sensor · Feedback · Cycling cadence

1 Introduction

Physical exercise can help to attenuate the incidence of the so-called age-related conditions (Valenzuela et al. 2011). More effective interventions based on personalized exercises and designing physical training programmes can improve the muscle strength and balance (Larsson et al. 2019). Recent studies reported that cycling training has positive effects on muscle strength, bone density, spasticity, cardiopulmonary function and many other physiological and psychological benefits in neurological patients and in the elderly. All the factors are directly related to improvement of functional abilities in postural control and gait (Peng et al. 2011).

Therefore, the need arises to identify new tools that allow to encourage physical activity and to promote adherence to functional activity programmes. Among the emerging technologies applied to this area, immersive technologies stand out. Their potential lies in the ability to generate controlled and personalized immersive environments where the movements made by the user can be captured and objectively quantified. Thus, we want to generate a virtual reality

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application that stimulates the user's sense of immersion as a way to promote adherence to a continuous exercise routine. The requirements for this virtual reality application must be: (i) that it can be used with any stationary pedalling system and therefore, (ii) that it does not depend on a specific system, (iii) that it can be used in a generic virtual reality helmet at an affordable price. And above all, that it is easy to install the pedalling system, which implies reducing possible sources of complications such as dependence on external systems and use of cables.

1.1 Immersive environments for indoor cycling training

The latest use of virtual reality technologies is aimed at providing feedback to stroke patients to improve cortical activity, functional performance, muscle control and fatigue (Ferrante et al. 2011; Yang et al. 2014). Among the possible modalities of extrinsic biofeedback adopted for stroke patients, visual input is the most widely used (Ebrahim 2000). Visual feedback during cycling could improve neuromuscular control and the overall training performance (Lin et al. 2012), which is generally based on cadence and load. The generation of cycling training home-based systems requires the integration of user-friendly and low-cost tracking systems, affordable game stations and common static bicycles or monocycles. To facilitate access to immersive environments for cycling, several mobile applications have been developed like Virtual Cycling World (World 2022) or Cycle Go (Software 2021) offer scenic roads and voice guided training to make indoor training more effective and enjoyable. These solutions do not monitor the user's exercise but seek to improve the user performance through virtualized environments and motivating feedback.

On the other hand, the approaches found in the literature in this field rely on high-cost robotic systems and complex and highly specialised equipment. Cardoso et al. (2019) developed a neurorehabilitation platform using a robotic monocycle instrumented with inertial sensors to measure cadence. They also customized an electronic board to control the virtual monocycle with user's motor imagery of electroencephalography (EEG) and surface electromyography (sEMG). Ferreira et al. (2019) developed an active-motorized static bicycle which can be gradually adjusted according to the pressure exerted on pedal's force sensors. This design allows to use different parameters to train each leg individually to compensate impairments. Chen et al. (2017) offered an integral solution that includes an electric wheelchair with lower limb training function, a multivariate control module, a virtual reality training module and a tele-doctor-patient interaction module. Despite specific hardware designed for lower limb rehabilitation combined with virtual or non-immersive scenarios, the most widely used equipment are static pedalling stations such as those marketed under the trademark MOTOMed™. In fact, Grani and Bruun-Pedersen (2017) developed a VR biking system, named Giro prototype, using a pedal-tracking device mounted on a MOTOMed™, which synchronizes the visual virtual feedback to user exercise.

1.2 Motion tracking for cycling

In the spirit of increasing the visual feedback of movement, approaches are emerging that seek to represent the user's virtual avatar through tracking systems. But representing the positioning and orientation of the user's body from a tracker data acquisition is still a very challenging issue. When it comes to full body tracking, most common VR approaches are limited by either high latency or insufficient accuracy. Regarding the features of the most advanced non-standalone HMDs, like HTC Vive™, PlayStation VR or Oculus Rift™, can detect the positions and rotations of their headsets and compatible controllers or trackers, since they use their own infrared tracking system (Farahani et al. 2016). These tracking solutions overcome the jittering and inconsistent tracking of fine movements as suffered by Kinect or Nintendo Wii (Friðriksson et al. 2016). But even all these motion-sensing models are limited by the occlusion principle to a greater or lesser extent, since the markers must remain within the space delimited by the tracking systems. Recent studies focus on the design of real-time gait tracking systems detecting for virtual reality rehabilitation training platforms. Nowadays, wearable sensors based on IMUs are widely used to monitor human gait. The list of applications of IMUs on gait analysis present by Ribeiro and Santos (2017) includes several prototypes and commercial solutions. This review identifies solutions that allow the estimation of thigh movements, the measurement of lower limb joint angles and the study of physical activity and postural orientation and the estimation of temporal parameters of gait. In addition to the applications of these sensors for the study of gait, it should be noted that the use of virtual reality in this field of study has promoted the development of solutions that provide interactive and attractive locomotor training (Kim et al. 2019) for the user or the patient. Therefore, some studies have simulated walking in different virtual environments (Fung et al. 2006; Yang et al. 2008) promoting different tasks, such as walking on a slope or walking while avoiding obstacles (Mirelman et al. 2011; Shema et al. 2014). As an example, Guo et al. (2017) analysed gait parameters relations to the plantar pressure and the lower limb joints range of motion (ROM) measured by inertial measurement units (IMU). The aim of this sensing system is to transmit the lower limb motor parameters of patients via bluetooth into the virtual training game, as the motion control signals for character driven in games has proved to be valuable in rehabilitation assessment. With the aim of capturing the user's movement using hardware-based virtual reality trackers: Caserman et al. (2019) proposed to synchronize avatar's motions with user's motions using HTC Vive™ headset and Vive Trackers™. They conclude that the imperceptible delay of 6.71 ± 0.80 ms and the reasonable accuracy of the tracking, according with the results of the rating simulation questionnaire based on Likert scale, were contributing factors in the user's perception of deep immersion. Besides the use of trackers and inertial sensors for capturing pedalling motion, the use of smartphone applications for monitoring outdoor pedalling or running has become widespread. APPs like Strava (2022) track the route by GPS and provide exercise performance information based on the device's internal accelerometer and gyroscope sensors, and often complement it with biometric data. These applications implement algorithms for real-time motion detection similar to those used in IMU sensors. For indoor cycling, APPs like ICG (Group 2022), OneLapFit (OneLap 2022) or BODY BIKE Indoor Cycling (BIKE 2022), among others, allow monitoring exercise performance, but these APPs are developed to be used for specific hardware, i.e. to be paired with a specific commercial exercise bike.

It is also worth to mention computer vision (CV) and video-based applications for tracking and visualizing the posture and movement of indoor pedalling. Kaplan et al. (2019) presented a video-based framework for cycling to enable tracking of the knee. This approach allows monitoring the trajectory that describes this joint in real time with the aim to visualize cycling biomechanics and to avoid overuse injuries. Bini et al. (2021) presented a solution for postural analysis during pedalling motion based on video analysis for detection of the body segments. This automated tool allows the analysis of the cyclist's biomechanics. With a similar approach, in automating real-time motion detection, Karashchuk et al. (2021) created a markerless CV-based tool able to analyse 3D walking kinematics in humans, mice and insects. In case of human gait characterization, this tool extracted knee flexion, hip rotation and hip flexion angles from 3D joint positions tracked. Although the latter solution does not focus on pedalling, it also illustrates the potential for motion tracking in the field of computer vision. Yet, it should be acknowledged that wearable inertial sensors have no disadvantages compared to vision systems, which may have tracking problems due to illumination or occlusion. Of course, inertial systems provide a direct measurement of joint motion rather than an estimation from image or video processing techniques. For these reasons, it becomes more intuitive and reasonable to use inertial systems to address motion tracking in pedalling.

1.3 Approach

While emerging technologies are being used to promote physical activity, many of these new therapies based on video games (Dimbwadyo-Terrer et al. 2016; Bayón and Martínez 2010) focus on two fundamental aspects: inducing as much immersion as possible and accurately tracking the user's movements. The potential of aiming these aspects is that enabling accurate tracking is necessary to evaluate whether the movements have been performed correctly and achieving greater immersion improves the user's engagement in a physical task. Current VR devices, by their very nature, are capable of very accurate tracking of the user's head and hand movements, but they rely on motion tracking systems to manage reliable and accurate data on any other body-segment. Nevertheless, rehabilitation solutions based on immersive environments are more effective than traditional (Viñas-Diz and Sobrido-Prieto 2016) because of these essential qualities: first of all, they have proven to improve individual engagement: Exergames increase user energy expenditure and involve both cognitively and physically rewarding tasks (Maillot et al. 2012). These highly motivating activities are likely to promote adherence to play. Secondly, they provide physical fidelity to a real movement: the user performs movements similar to what he or she would do in an analogous situation during daily life. And lastly, they provide cognitive fidelity to a real situation: The person must perform the activities in an environment designed to be similar to the real world.

With all this in mind, it is still necessary to generate an accurate cycling motion capture system that is universal to any cycling equipment and communicates with a virtual reality application on any standalone device. Therefore, the present work seeks to provide an approach that allows to accurately track the pedalling movement of the individual (i) without limitations of occlusion in the tracking and (ii) without defining the initial orientation of the person's body, but (iii) ensuring low-latency tracking for real-time applications, and (iv) a virtual reality solution specifically design to be motivating to perform pedalling exercises. Hence, we have developed a low-cost wireless standalone platform for VR-based cycling exercises using an IMU paired with the Oculus Quest 2 headset and a common stationary bicycle, which is expected to promote immersion and improve individual engagement to the PA therapy.

The overall objective of this work is to present a low-cost wireless application in virtual reality (VR) for pedalling exercises. This is addressed in the following points: the first is to describe our technical approach according to the mentioned design features to increase user motivation. The second one is to technically evaluate the validity and reliability of our cycling cadence estimation system for real-time exercise feedback in virtual scenarios. For this technical validation, we have tested with healthy participants our approach by assessing the validity and reliability of the cadence estimation outcomes related to another cycling platform set as reference.

2 Materials and methods

2.1 Description of the cycling platform used as reference

The reference cycling platform was composed of a magnetic encoder (AS5048, AMS AG) attached to the rotation axis of the MOTOMed™Viva2 with an analogue potentiometer (modelled as a linear transducer between 0° and 360°) plus a microprocessor (STM32F302K8, STMicroprocessors) that reads each 20 ms the encoder and sends the pedalling angle value via CAN communication protocols to a microcontroller (Arduino Uno) for the real-time reading of the crank angle position loop. To enable the Arduino UNO to receive CAN messages, a CAN shield (SparkFun Electronics, Boulder) was installed on the Arduino, taking advantage of the capability of modular extensions of this microcontroller. When Arduino UNO microcontroller receives the pedalling angle via CAN communication, it sends it simultaneously to the PC interface via USB (see Fig. 1).

2.2 Development of virtual reality pedalling platform

The virtual reality pedalling platform consists of two parts: the ENLAZA™ sensor (Werium Assistive Solutions) as the main sensing system which integrates microcontroller unit (MCU), inertial measurement unit (IMU) and a Bluetooth module, and a virtual rehabilitation training scene built for Oculus Quest 2™(Facebook Technologies, LLC), as shown in Fig. 2. In order to meet the portable requirements, the Oculus Quest 2 has been selected as a low-cost, portable, commercial standalone VR device that allows the pairing of peripherals via Bluetooth. The sensing system used was the ENLAZA™ sensor from Werium Assistive Solutions, due to its proven reliability of their ROM measurements in wrist and elbow joints (Costa et al. 2020).

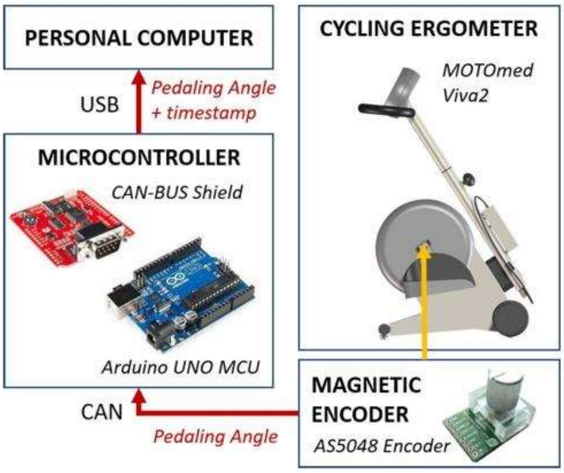

Fig. 1 Diagram of the cycling platform system set as reference for the comparison study

The ENLAZA™ sensor module contains an IMU with 9 degrees of freedom; which integrates a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer. The sensor module also includes a microcontroller unit (MCU) (8-bit AVR, 8 MHz, 32 KBytes of flash memory) to acquire the raw data of all three sensors via I2C protocol and to compute the angular orientation (yaw, pitch and roll) and the Direction Cosine Matrix (DCM) at 50 Hz before forwarding it via UART at 57,600 Kbps to the Bluetooth module (2.4 GHz, class 2 radio, 20 m range, slave mode and on-chip antenna). Additionally, the transmission settings of the ENLAZA™ sensor were adapted to implement a serial transmission protocol of binary data packages to feed the estimation algorithm. The modification consisted on sending data over a single byte-by-byte communication path from the built-in Bluetooth module of the sensing system to he VR headset. The rotation data are transmitted in binary format in 48-byte buffers to the VR HMD and, once all received on VR application, first 12-bytes are parsed into (single type) 3×1 Vector, to save the angular velocities, and last 36-bytes are parsed into a (single type) 3×3 matrix to construct the rotation matrix. From this rotation matrix, the hip flexion-extension angle is calculated, allowing to analyse the pedalling motion in the sagittal plane. The following sections detail how this angle is calculated and how all the input signal is processed for the estimation of the cadence.

2.2.1 Definition of coordinate system

To describe the orientation of a body-fixed coordinate frame many possible sets of generalized coordinates can be used. For our purpose, we based the cadence estimation on the kinematic model of the hip. To describe the orientation of the tight according to the convention recommended by the International Society of Biomechanics (ISB) for the femur, we adopted the standard coordinate system (Wu et al. 2002), where the Y axis is defined along the line joining the hip centre and the midpoint of the medial and lateral femoral epicondyles, pointing proximally. The Z axis is perpendicular to the Y axis, located in the plane defined by the hip centre and both femoral epicondyles, pointing laterally to the right side of the body. The X axis is then perpendicular to both, pointing ventrally (anteriorly). Flexion would therefore be defined

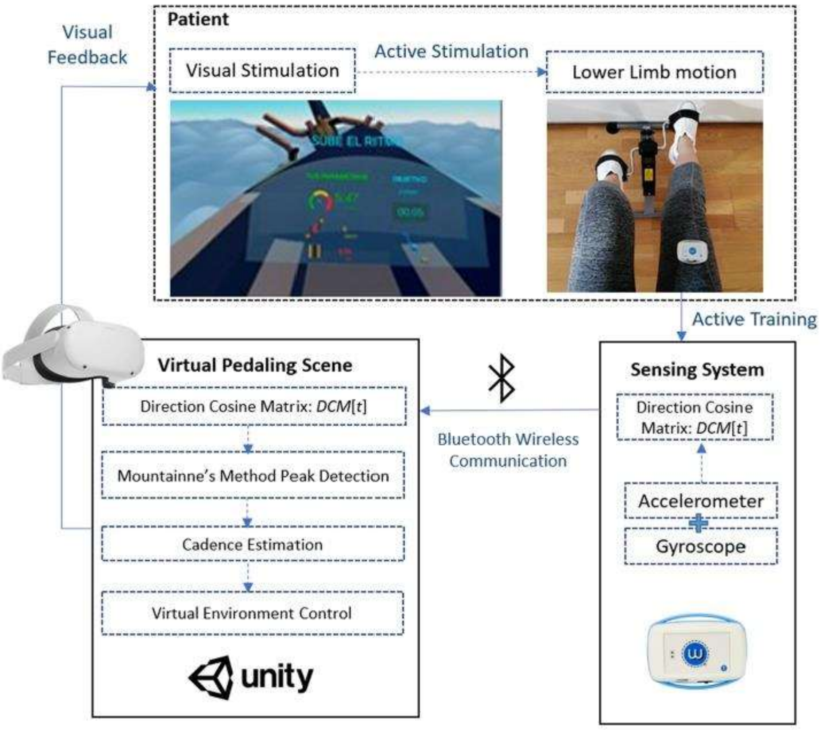

Fig. 2 Overall scheme diagram of the developed virtual cycling platform to be validated

around the Pelvic Z axis, axial rotation around the Femoral Y axis, and adduction/abduction around the "floating" axis mutually perpendicular to the Pelvic Z and Femoral Y axes. Relating the ISB coordinate system to the own reference coordinate system of the IMU sensor as shown in Fig. 3, it is obtained that $Y_{\text{ISB}} = X_{\text{IMU}}$, $Z_{\text{ISB}} = Y_{\text{IMU}}$ and $X_{\text{ISB}} = Z_{\text{IMU}}$.

2.2.2 Estimation of the hip flexo-extension

The first step of our approach is to calculate the Direction Cosine Matrix (DCM) at the IMU sensor. We obtain the DCM fusing the accelerometer and gyroscope signals following the method proposed by Premerlani and Bizard (2009).

Then, we send the DCM data to de virtual cycling platform (VCP) via WiFi. To estimate the neutral position of the sensor in virtual world coordinates, we first determine a calibration matrix to set this new reference frame. To calculate the transformation matrix for each movement, we multiply the transposed calibration matrix ($R^{\text{T}}_{\text{cal}}$) with the DCM ($R_{\text{raw}} \in \mathbb{R}^{3\times3}$), transmitted from the IMU sensor, at time step t to obtain the transformation matrix (R_{trans}), which describes in Unity's local coordinate system the rotations performed by the sensor. This is applied according the following equation: $R_{\text{trans}}[t] = R_{\text{raw}}[t] \times R^{\text{T}}_{\text{cal}}$, where R_{cal} is the calibration matrix, R_{raw} is the DCM matrix obtained by the IMU sensor, and R_{trans} is the final matrix after applying the calibration. After calculating R_{trans}, we normalize it, so that the system is orthonormal. The R_{trans} normalized is described as a 3×3 matrix whose elements represent the angles of the 3 axes for each of the planes of rotation:

$$R_{\text{trans}}[t] = \begin{bmatrix} r_{00} & r_{01} & r_{02} \\ r_{10} & r_{11} & r_{12} \\ r_{20} & r_{21} & r_{22} \end{bmatrix} \in \mathbb{R}^{3\times3} \tag{1}$$

Reconciling the rotations of the $R_{\text{trans}}[t]$ calibrated rotation matrix with Euler angles, it would correspond as follows: rotation in Y-coordinate axis represents flexion/extension movement, rotation in Z-coordinate axis represents the adduction/abduction movement, and the rotation in X represents the axial rotation movement around the femoral axis, satisfying the relations described in (1):

- *hip adduction/abduction angle*: $\psi = \arcsin(-r_{01})$
- *hip rotation angle*: $\phi = \arctan 2(r_{21}, r_{11})$
- *hip flexion/extension angle*: $\theta = \arctan 2(r_{02}, r_{00})$

2.2.3 Cadence estimation algorithm

Relying on the timed interpretation of rotation, data describes the cycling motion curve, where cycling-phase angle could be known from processing hip flexion-extension angles. Taking the sequence of rotation angles over time as

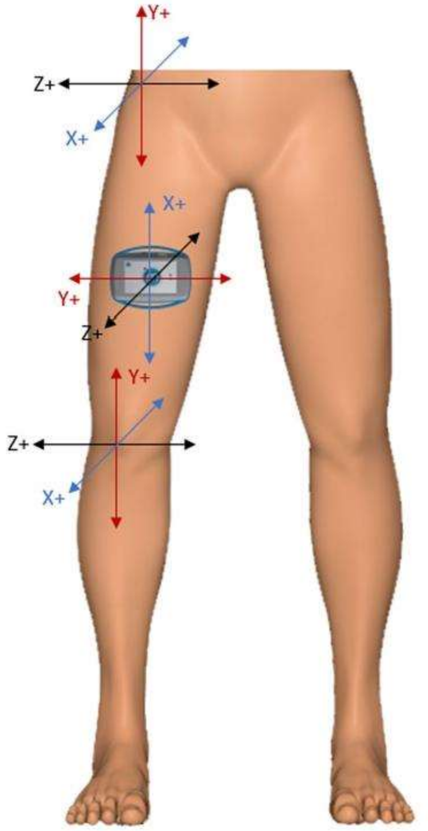

Fig. 3 Coordinate system relation between ISB and own reference coordinate system of IMU sensor

the samples of a motion function, the number of cycles can be counted as number of peaks detected along the signal.

Cycling phase analysis is here formulated as a peak detection problem using the mountaineer's method for peak detection (MMPD) (Argüello-Prada 2019). Our MMPD-based method consists of considering all cycles as mountains, and then the peaks of the mountain will be the crests of the curve. Thus, each detected peak will represent the starting session of a cycle. The pseudo-code of this method is shown in Fig. 4, in which all flexion-extension angles are added to an $N \times 1$ array (*alfa* array at Fig. 4) each batch of 3 samples data are analysed. At each batch, samples are classify as maxima or minima, and the maximum local value is set with the highest value among those. Once a local maximum is reached, the cycle-counter is incremented by one and the value of the maximum is reset to the value of the symmetry axis. This way, when the curve starts its positive phase again, the local maximum is searched for again by analysing the values of its segment neighbours. To avoid peak detection failures due to baseline changes, the symmetry axis threshold is adjusted from the average of the amplitude values of the last 1000 ms with a 20 ms refresh rate.

2.2.4 Virtual platform

Virtual rehabilitation training scenes are programmed with Unity3D software platform for Android 25 API Level for Oculus Quest 2 HMD. The user actives the ENLAZA™sensor to provide motion control signals for the game scenarios. Meanwhile, the user acquires the visual feedback information, so as to maintain or adjust the cycling cadence in order to achieve the best training effect. The user is able to be aware of the cycling assessment results promoted by the rehabilitation evaluation module in real time.

In this game, the user is in the steer cab of a vehicle which moves forward at user's cycling speed. The user has to pedal at a fixed target speed. Therefore, derived from cadence estimation (see Sect. 2.2.3), the following information about cycling performance is displayed on a panel in text format to strength engagement experience:

Fig. 4 Pseudo code of discrete sample's method peak detection

```
//**Initialization**//
localmax = alfa[0]  threshold = average  //**Peak detection loop**//
loop
if $alfa.Count \geq 2$ then
    while $isCycling == true$ do
        $getsample(i)$ if $sample(i) \geq threshold$ & $sample(i) \geq localmax$ then
            $localmax = sample(i)$
        end
        if $sample(i-1) == localmax$ & $sample(i-2) \geq sample(i-1)$
        & $sample(i) \leq sample(i-1)$ & $sample(i) \geq threshold$ then
            $cycles++$  $localmax = threshold$
        else
            $localmax = threshold$
        end
    end
end
end loop
```

- *Number of crawl cycles* cycle-counter of peak detection (see Fig. 4).
- *Distance travelled* the estimation of forward displacement depends on the number of cycles and virtual wheel radius (27 cm) as: $\text{distance (km)} = \lfloor(2.0f \times \pi \times 0.27\,(\text{m})) \times N_{\text{cycles}}\rfloor/1000$
- *Pedalling speed* Knowing that $\omega\,(\text{rad/s}) = v\,(°/\text{s}) \times 2\pi/360$; the formula applied to calculate pedalling speed for each time lapse between cycles is: $\Delta v\,(\text{km/h}) = \left|(2.0f \times \pi \times 0.27)\,(\text{m})/\Delta t\,(\text{s})\right| \times 3.6$; setting an average wheel radius of 27 cm.
- *pedalling Pace feedback* compares each frame whether average pedalling speed is equals to ($\pm 10\%$) target speed; higher than ($+10\%$) target speed; or lower than (-10%) target speed; according to this classification, either one feedback message is displayed to user's to keep, reduce or increase cycling pace.
- Also *elapsed time and target speed* are displayed to remind the game objectives to the user.

In addition, the speed information is mapped to those elements of the virtual environment that are moved to generate a perception of displacement. Also, shader-based procedural terrains have been used to optimise the graphics rendering of the experience. This has made it possible to keep the static virtual camera embedded within the vehicle model and to simulate the displacement of the environments by varying the exposed variables of the texture displacement velocity shaders on the forward axis. Lastly, the whole experience is designed for Hand-Tracking enabling a soft user-interface based on touch panels.

2.2.5 Software strategy design

Visual feedback is extremely important to any VR experience, even more so in extrinsic feedback where processing latency and rendering times must be optimized to the maximum in order not to compromise the feeling of immersion. The CPU and GPU performance of the HMD must be considered in the design of the VR experience development to ensure its functionality. The Oculus Quest 2 was launched with the Qualcomm Snapdragon XR2 platform, expanding the overall AI processing power and improving the engine of visual analytics (EVA) to reduce latency and support stronger connectivity. Exploiting these technical improvements, our application design involves the following features: (i) modulate the whole virtual environment based on cycling speed and (ii) enable interaction via hand-tracking. In order not to compromise visual results, the threads-tasks for communication and processing data have to be optimized.

Regarding our cadence estimation algorithm, it has to be executed, at least, every 10 ms to grant accurate feedback in real-time. To meet this requirement, our MMPD-method has been implemented with timer events because it was tested that including the call to the MMPD-method in the 'Update' function of Unity's MonoBehaviour classes compromised the rendering frequency of the application. Worse results were obtained with the use of background threads. This strategy does not compromise the performance of the CPU and optimizes the execution of the MMPD every 10 ms without affecting the performance of the VR application with an average rendering rate of 70–75 FPS. The signal analysis optimization strategy has been an important issue, as it must compensate for the sampling rate of the IMU. It should be recalled that the data acquisition times by the IMU sensors and the composition of the DCM for the transmission of information via Bluetooth takes 20 ms. In addition, the latency in the Bluetooth reception and processing of the message for the flexo-extension angle calculation adds 10 ms, resulting in a 30 Hz data capture rate. Due to this limitation in frequency of the setup, it has been necessary to achieve an optimal cadence analysis algorithm that does not saturate the performance of the device so as not to affect the rendering frequency.

On the other hand, a virtual reality environment has been generated in which the aeroplane velocity and flight altitude are directly influenced by the user's speed and cadence stability. With these interrelations of effects, the user can observe how the conditions of his flight vary depending on his pedalling performance. This approach of using proprioceptive stimulation in VR as a strategy to involve the user in the physical activity has been previously explored by Grani and Bruun-Pedersen (2017) and Guo et al. (2017). All in all, these studies have shown that this strategy achieves a high sense of presence in the user and enhances engagement in the physical activity promoted. Bringing it to this context, our application is not only a 3D digital environment in which user's pedalling parameters are shown in real time, but it is also an experience that allows the user to modulate how the vehicle behaves within the game. Therefore, the user is expected to be involved in achieving and maintaining the target speed during the session and also to control the behaviour of the vehicle. In the end, relating the participant's exercise performance to the behaviour of the vehicle and, by placing the user in first-person control of the game, it is expected that the user will perceive all changes in the environment with greater impact than through a screen, which is the most commonly employed system.

2.3 Study design

2.3.1 Participants

The committee of CEU San Pablo University provided ethical approval for this research (Trial reference: 550/21/51).

Participants were recruited via email by contacting those people subscribed on the list to participate in studies of the NeuroRehabilitation Group of the Cajal Institue, Spanish National Research Council (CSIC). Thirteen participants (nine men and four women, aged 25.38 ± 1.14) volunteered to participate in this study. They were informed about all the procedures and possible discomforts before giving their informed consent. The following criteria were applied for the selection of participants for the study.

- Inclusion criteria: (i) Healthy physical condition, (ii) Ability to follow instructions. (iii) Ability to perform pedalling movements.
- Exclusion criteria of participants: (i) Visual problems that cannot be overcome by the use of contact lenses or glasses compatible with the usage of VR HMD. (ii) Presence of any pathology or joint disorder affecting lower limb movement. (iii) Predisposition to suffer dizziness or loss of balance. (iv) Altitude sickness. (v) Failure to sign the informed consent form.
- Withdrawal criteria: (i) Decision by the participant to drop out. (ii) Feeling dizzy during the test due to visual incongruities. (iii) Feeling of discomfort or fatigue due to physical exercise.

2.3.2 Data collection system

The system configuration taken during the experimental study is the shown at Fig. 5. We set up the virtual platform with the ENLAZA™ sensor, an Oculus Quest 2™ and a stationary bike provided with a hall effect sensor connect to an Arduino UNO microcontroller that triggers the angle of pedal position each nanosecond. That Arduino is connected to a PC running an specific software to read the Arduino serial port, clean incoming readings and save the amount of cycles performed. In order to synchronize the VCP and the pedalling platform of reference in the pedalling trials,

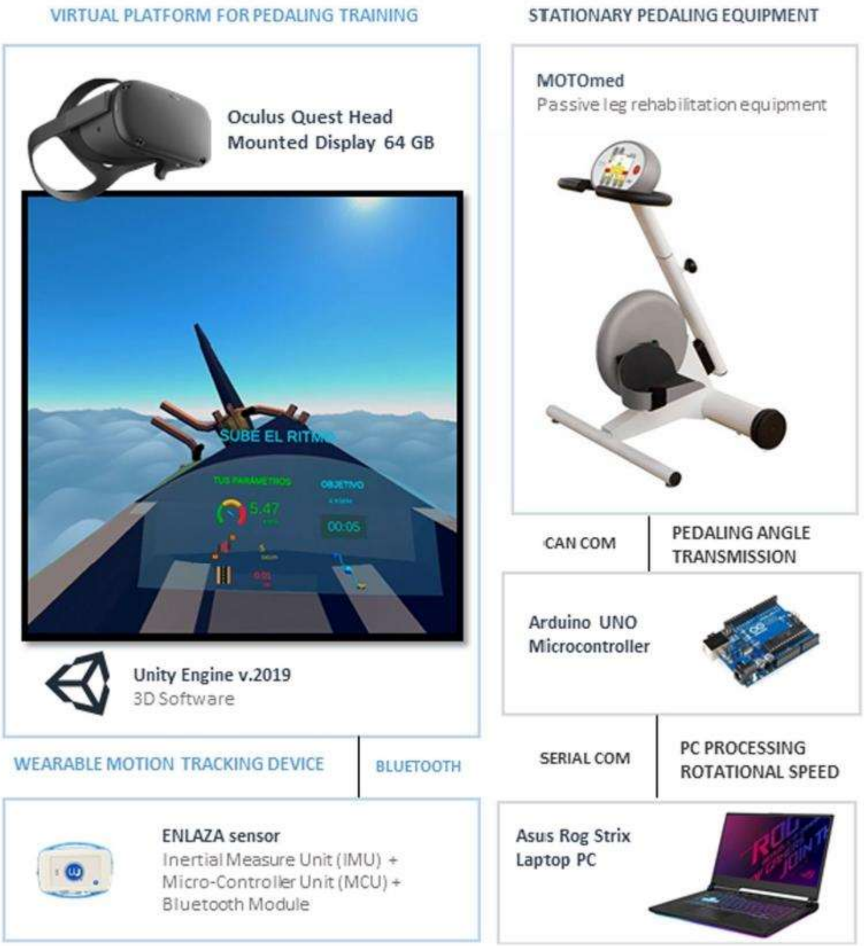

Fig. 5 Overview of the components of both systems used in the validation study. The left side of the diagram shows the elements of VCP, and the right side shows the elements of the reference pedalling system

since the VCP is a closed-loop system, both systems had to be initiated simultaneously at each attempt by the user via pressing a keyboard button with one hand and a virtual button with the other hand.

2.3.3 Procedure

Preliminary preparation Prior to placing the physical elements of the test on the participant, the ENLAZA™ sensor had to be paired via Bluetooth with the Oculus Quest 2™. Then, the sensor was placed on the participant's thigh by adjusting the elastic-strap and ensuring its correct orientation. Once the subject sat in a chair with the feet secured to the pedals of the ergometer, the Oculus Quest 2 HMD was adjusted to the user's head by widening or narrowing the elastic bands.

According to this arrangement, the design of the commercial motorized ergometer and the positioning of the subject, maximum knee extension was reached at 90° crank angle, maximum knee flexion at 270°, maximum hip extension at 140° crank angle, and maximum hip flexion at 320° crank angle. As 0° or 320° crank angle corresponds to the position when the pedal is in its top position and 180° to the pedal bottom position. Therefore, it is expected to obtain a minimum hip flexion about 30° and a maximum hip flexion about 70° according to normal ranges of hip flexion during city bike cycling movement (De Roeck et al. 2021).

Pedalling trials procedure Prior to the experimental trials, all the participants performed a 2-min warm-up of pedalling to familiarise with the virtual platform. Then, the experimentation is organized in two identical sessions in which participants performed 3 sets of pedalling at a constant speed of 30 rpm, 60 rpm and 90 rpm with 3 min rest between sets. Also, each set is divided in 3 trials of 1 min cycling, in order to assess the number of cycles 3 times per each target speed. After 30 min of resting, we repeated the whole session, assuming this lapse of resting time to be sufficient to allow this second round of pedalling exercises to be considered as an independent sample. In each trial, the participants were told the target speed to cycle at and to maintain it based on the information displayed on the vehicle's control panel and the aeroplane's behaviour.

3 Results

This study aims to evaluate the performance of our development in terms of cadence estimation accuracy. For this purpose, we carried out the analysis of the correlation and reliability of the cadence results between our development and the pedalling system developed previously, as a reference. The statistical analysis was performed using IBM SPSS Statistics, version 27. Due to the low sample size, the Shapiro–Wilk test will be applied to confirm the normal distribution of our data, with a significance level of $p \leq 0.5$. For each subject and session, 3 samples of each speed were taken to generate the descriptive statistics shown in Table 1. Each test consists of 1 min of pedalling. Thus, the mean and standard deviation of each set of speeds for 1 min of pedalling is calculated.

Table 1 Session 1: Sample mean ($\bar{x}$) and standard deviation (σ) of cycles per minute at target Speed 30 rpm, 60 rpm and 90 rpm

N	Speed = 30 rpm		Speed = 60 rpm		Speed = 90 rpm	
N	MOTOMed	VCP	MOTOMed	VCP	MOTOMed	VCP
	($\bar{x}\pm\sigma$)	($\bar{x}\pm\sigma$)	($\bar{x}\pm\sigma$)	($\bar{x}\pm\sigma$)	($\bar{x}\pm\sigma$)	($\bar{x}\pm\sigma$)
1	31.66 ± 1.52	32.00 ± 0.00	60.00 ± 0.00	59.66 ± 0.94	90.00 ± 0.82	88.00 ± 3.56
2	33.66 ± 0.57	33.00 ± 1.73	60.33 ± 2.86	60.00 ± 1.41	95.00 ± 1.63	89.66 ± 1.88
3	31.33 ± 2.08	31.00 ± 5.57	61.33 ± 0.47	61.33 ± 2.05	90.00 ± 2.16	88.00 ± 0.82
4	32.33 ± 1.15	32.66 ± 0.57	60.33 ± 0.47	60.66 ± 0.47	91.00 ± 2.16	88.66 ± 1.25
5	31.33 ± 0.57	32.00 ± 1.73	61.00 ± 1.63	61.33 ± 1.69	93.00 ± 4.96	89.00 ± 1.4
6	32.00 ± 2.64	31.66 ± 6.02	60.66 ± 0.47	60.66 ± 1.24	90.33 ± 1.88	85.66 ± 0.47
7	29.66 ± 1.15	30.33 ± 0.57	61.66 ± 0.47	61.00 ± 0.00	87.66 ± 0.47	84.66 ± 0.47
8	29.33 ± 1.53	29.33 ± 2.31	59.66 ± 0.94	58.33 ± 2.05	87.66 ± 1.25	86.00 ± 5.65
9	29.00 ± 1.00	28.33 ± 1.52	59.33 ± 2.36	58.66 ± 4.03	87.33 ± 0.47	83.66 ± 1.25
10	29.33 ± 1.15	29.00 ± 2.00	62.00 ± 0.82	61.66 ± 2.49	88.667 ± 0.47	84.00 ± 0.82
11	31.66 ± 2.08	31.66 ± 2.08	61.33 ± 2.05	60.66 ± 1.25	88.66 ± 0.47	85.00 ± 0.81
12	29.33 ± 1.52	29.33 ± 2.52	59.33 ± 0.47	57.66 ± 0.47	89.00 ± 0.82	83.66 ± 1.24
13	33.00 ± 1.73	32.66 ± 1.53	58.66 ± 0.47	58.00 ± 0.82	90.00 ± 1.41	88.33 ± 0.94

3.1 Visualization of cadence estimation algorithm performance

Average hip ROM curves have been generated for a pedalling cycle at 30 rpm, 60 rpm and 90 rpm. Figure 6 shows that the hip flexion values performed during cycling exercises on the virtual platform are in accordance with the normal range of motion(Ericson et al. 1988) as predicted for this activity .

Figure 7 illustrates the relationship between the number of samples and the pedalling cadence for different speeds. Each point on the curves in the graph represents a sample taken by the inertial sensor and processed by the VR HMD, and each curve represents the hip flexion angles captured during pedalling at different set speeds. Considering that at all times, and acknowledging that the system has a sampling rate of 30 Hz, it is expected to observe that a 30 rpm cadence cycle has a similar number of samples to 2 cycles of 60 rpm cadence and, in turn, to 3 cycles of 90 rpm cadence. This implies that for high pedalling speeds, each pedalling cycle is described with fewer samples due to the constant data capture rate (30 Hz).

This fact is also observed in the generation of the average hip flexion curve for one pedalling cycle (Fig. 6). For 90 rpm a smoother curve is observed due to the scarcity of

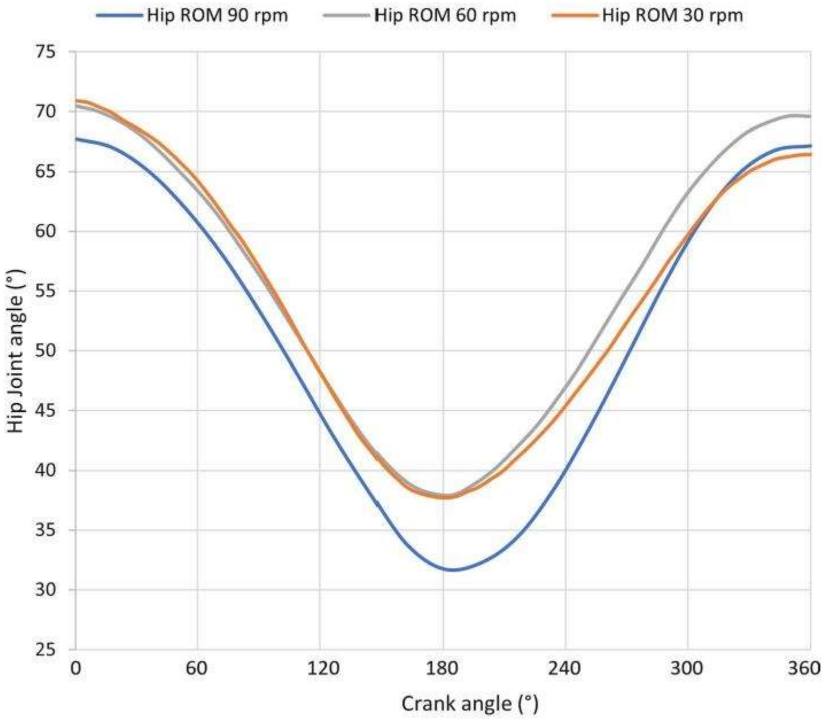

Fig. 6 Mean hip joint range of motion (degrees) during ergometer cycling at the three set speeds: 30 rpm, 60 rpm, 90 rpm

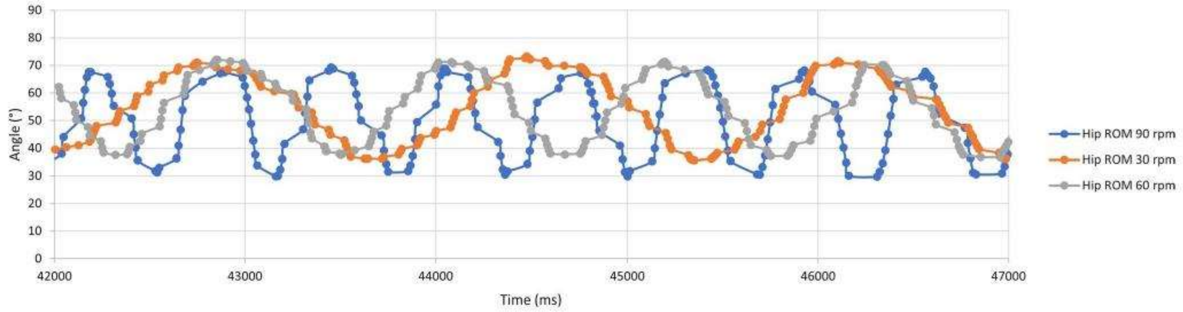

Fig. 7 Five second time plot (ms) of hip ROM capture by the VCP during pedalling exercise at the three set speeds. The dots plotted along the curves represent each sample taken by the IMU and processed by the VCP in real-time during exercise

samples along the slope, while for 30 rpm an average curve with smaller oscillations is observed, due to a higher amount of samples.

3.2 Validity evaluation of cadence estimation algorithm

The validity of the algorithm can be understood as the proportion of number of cycles that are correctly detected according to the number of cycles measured by the reference cycling platform. Therefore, the higher the correct rate, the more the algorithm accuracy is. The assessment of these proportions can be established by correlating the cycles averages of the VCP against the sample averages of the MOTOMed™ cycles. The formula used to calculate this correlation coefficient is:

$$\mathrm{Correl}(X, Y) = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}} \tag{2}$$

where $\bar{x}$ and $\bar{y}$ are the detected cycles averages of the algorithm method and the measured cycles averages of the MOTOMed™. To assess the validity of the cadence estimation system, we applied the correlation coefficient of Spearman for each of the target speeds, taking a confidence interval (CI) of 95%, between the measures taken simultaneously. Also, the normal distribution of the data has been verified for all groups.

Involving all the trials in the two sessions, Spearman correlation value for MOTOMed™-VCP algorithm for target speed of 30 rpm was 0.946 ($p \leq 0.001$ with 95% CI ranged 0.818 to 0.985) for the first session and 0.858 ($p \leq 0.001$ with 95% CI ranged 0.571 to 0.958) for the second session. In general, for both sessions, the correlation values indicate a high correlation between the results of both pedalling systems at a cadence of 30 rpm. Spearman correlation value for MOTOMed™-VPC for each session at a target speed of 60 rpm was 0.931 ($p \leq 0.001$ with 95% CI ranged 0.772 to 0.980) and 0.895 ($p \leq 0.001$ with 95% CI ranged 0.669 to 0.970), respectively. These values point out a high correlation between the cadence estimation performance of both systems at a cadence of 60 rpm. Finally, the Spearman correlation value for MOTOMed™-VCP for each session at a target speed of 90 rpm was 0.787 ($p = 0.001$ with 95% CI ranged 0.401 to 0.935) and 0.760 ($p = 0.003$ with 95% CI ranged 0.344 to 0.927). Since the correlation outcomes are less than 0.8, it is considered a moderate correlation between both pedalling systems at a cadence of 90 rpm. These results illustrate that several cycles are not detected by the VCP at a 90 rpm, as shown in Tables 1 and 2 (Table 3).

Table 2 Session 2: Sample mean ($\bar{x}$) and standard deviation (σ) of cycles per minute at target speed 30 rpm, 60 rpm and 90 rpm

N	Speed = 30 rpm		Speed = 60 rpm		Speed = 90 rpm	
N	MOTOMed ($\bar{x}$±σ)	VCP ($\bar{x}$±σ)	MOTOMed ($\bar{x}$±σ)	VCP ($\bar{x}$±σ)	MOTOMed ($\bar{x}$±σ)	VCP ($\bar{x}$±σ)
1	29.00 ± 5.29	29.33 ± 2.88	60.33 ± 1.24	59.66 ± 2.36	89.33 ± 0.47	87.33 ± 2.62
2	33.00 ± 2.64	33.66 ± 2.88	60.00 ± 1.41	59.33 ± 0.94	93.00 ± 0.82	90.00 ± 0.82
3	29.33 ± 1.15	28.66 ± 0.57	58.66 ± 0.47	58.00 ± 0.81	90.00 ± 1.41	88.33 ± 0.94
4	33.33 ± 1.15	32.66 ± 1.53	60.66 ± 0.47	59.66 ± 0.94	90.66 ± 0.94	85.00 ± 0.82
5	30.00 ± 1.00	29.00 ± 2.64	60.33 ± 0.94	60.33 ± 0.47	90.33 ± 1.24	85.33 ± 0.47
6	31.33 ± 0.57	32.00 ± 2.00	60.66 ± 0.47	60.66 ± 1.25	91.00 ± 2.16	85.66 ± 3.09
7	32.66 ± 3.21	31.66 ± 5.13	61.00 ± 1.41	60.66 ± 0.47	87.66 ± 0.47	83.33 ± 0.47
8	30.00 ± 1.00	29.66 ± 0.58	59.33 ± 0.47	59.00 ± 0.00	87.66 ± 1.24	83.00 ± 0.82
9	29.66 ± 1.15	30.00 ± 1.00	60.33 ± 0.47	60.00 ± 0.82	87.66 ± 1.24	83.66 ± 0.47
10	29.33 ± 0.58	29.00 ± 1.00	59.66 ± 0.94	59.00 ± 0.81	89.66 ± 1.69	84.33 ± 0.47
11	31.00 ± 0.00	31.00 ± 1.00	61.00 ± 0.00	60.33 ± 0.47	89.33 ± 0.47	86.00 ± 0.82
12	29.33 ± 0.57	29.66 ± 1.53	59.66 ± 1.25	59.33 ± 1.25	88.33 ± 0.47	83.00 ± 0.82
13	32.33 ± 1.15	32.66 ± 0.58	59.00 ± 0.82	59.33 ± 0.94	91.00 ± 2.16	88.66 ± 1.24

Table 3 Spearman correlations, 95% confidence interval and significance between MOTOMed™-VCP organized for target speed (30 rpm, 60 rpm, 90 rpm) and sessions (session 1–session 2)

	Session 1			Session 2		
	Spearman	Sig. (bilateral)	95% CI	Spearman	Sig. (bilateral)	95% CI
Speed = 30 rpm	0.946	≤ 0.001	[0.818 , 0.985]	0.858	≤ 0.001	[0.571 , 0.958]
Speed = 60 rpm	0.931	≤ 0.001	[0.772, 0.980]	0.895	≤ 0.001	[0.669, 0.970]
Speed = 90 rpm	0.787	0.001	[0.401 , 0.935]	0.760	0.003	[0.344 , 0.927]

3.3 Reliability evaluation of the systems

To evaluate the reliability of the measures collected by both systems, we calculated the standard error of measurement (SEM) and repeatability of the measurements using intraclass correlation coefficients (ICC), interpreted as a test-retest analysis. The ICC model (3,1) or Two-Way Mixed Effect model (Absolute Agreement Definition) described by Shrout and Fleiss (1979) was chosen because it considers random effects on the measurements over time (between session 1 and session 2). SEM can be estimated from ICC (Weir 2005):

$$\mathrm{SEM} = \mathrm{SD}\sqrt{1 - \mathrm{ICC}}, \tag{3}$$

were SD is the standard deviation of the measures. Reliability data are provided in Table 4.

The ICC values ranged between 0.416 and 0.913 involving all the speeds. At a target speed of 30 rpm the ICC values for the MOTOmed and the VCP are 0.743 to 0.746, respectively, and SEM values are 1.02 and 1.16 cycles, respectively. Something similar happens at a target speed 60, which ICC values for each system (MOTOmed and VCP) 0.416 and 0.445, and SEM values are 0.96 and 1.26, respectively. According to these results, at speeds between 30 and 60 rpm, the SEM outcome indicates a measurement error of about 1 cycle for each system. This is consistent with previous correlation results, which reflected the high correspondence in measurements of both systems at these speeds. However, in terms of repeatability, we observe that the ICC values are relatively low for both systems. The fact that both systems show consistency in repeatability indicates that both are affected by the same factors. We attribute these results to the human factor because, given that the tests have been performed with humans, despite their attention to maintaining the cadence, they do not achieve the same number of cycles in all sets, affecting the repeatability results. In contrast, at a target speed of 90 rpm, the ICC values are 0.913 and 0.851 for each system and SEM values are 0.799 cycles for the MOTOmed and 3.24 cycles for the VCP. In this case, the repeatability results show that for both sessions the systems have shown similar measurements, suggesting that both systems have been consistent with their measurements and that participants have been consistent with their cadences. However, it is evident for the VCP system that a target speed of 90 rpm its measurement error is 3 times higher than that of the MOTOmed.

4 Discussion

The objective of the present study was to test the validity and reliability of using a novel virtual reality HMD (Oculus Quest 2) in combination with a wearable IMU sensor placed on subject's tight to assess cycling cadence. To study the validity of this system, it is confronted against a reference pedalling platform previously developed and validated as a reliable cycling platform (Piazza et al. 2018). In this way, the cycle detection measurements performed by both systems during trials of 3 repetitions of 1 min of pedalling at 3 different set-point speeds (30 rpm, 60 rpm, 90 rpm) are captured simultaneously.

We highlighted the high concordance between the measurements taken by the cycling platform of reference (referred to as MOTOmed) and Virtual Cycling Platform (referred as VCP) for slow (30rpm) and medium (60rpm) speed in both sessions (Spearman Correlation Session 1: 0.946 and 0.931; Spearman Correlation in Session 2: 0.858 and 0.895). It has also been shown that the correlation is lower between the results of the reference platform and the system developed for 90 rpm (Spearman correlation session 1 = 0.787 and Spearman correlation session 2 = 0.760). This correlation result is attributed to the fact that at higher pedalling speeds more cycles are lost by the MMPD algorithm. While these results influence the accuracy of the pedalling cadence estimation, the algorithm is still quite successful overall as shown in the average results of Tables 1 and 2. As can be seen in the Fig. 7, at 90 rpm the movement is more shaky than at 60 or 30 rpm, simply because of the speed factor. High-speed pedalling exercises can result in a more unstable motion, which is reflected in the 90 rpm curve itself with a more staggered and less fluid shape. Small oscillations around the peak cause the algorithm to fail in cycle counting, as it is sensitive to the detection of local minima and maxima. This explains why the pedalling speed influences the cycle detection accuracy of the cadence estimation algorithm as shown in the outcome Tables 1 and 2.

Reviewing the repeatability results, it is observed that in the case of the MOTOmed, for all speeds the error in the measurement is around 1 cycle, while in the case of the VCP

Table 4 ICC (with 95%) and SEM for cycles measurements between sessions taken by the MOTOMed and the VR cycling platform (VCP) organized by target speed

Speed	MOTOmed				VCP			
	ICC	95% CI	Significance	SEM	ICC	95% CI	Significance	SEM
30 rpm	0.743	[0.083 , 0.855]	0.015	1.021	0.746	[0.173, 0.922]	0.014	1.16
60 rpm	0.445	[− 0.649 , 0.825]	0.151	0.96	0.416	[− 0.871, 0.821]	0.183	1.26
90 rpm	0.913	[0.719,0.973]	≤ 0.001	0.799	0.851	[0.504, 0.955]	≤ 0.001	3.24

it coincides with the previous one at speeds 30 and 60, but the error in the measurement amounts to 3.24 cycles at 90 rpm. It is also concluded that at speeds 30 and 60 the repeatability of the systems is slightly less consistent, although we attribute this to the human factor. Indeed, during the experimental trials, it was observed that at low to medium speeds, the participants are comfortable with the physical exercise and, due to the involving nature of virtual reality, they were often distracted by the virtual environment. However, at high speed, they focused all their attention on the pedalling due to the concentration required to maintain this speed. Therefore, the results of the ICC show that at high speed the VCP consistently exhibits cycle detection errors. But it also reflects the irregularity of the participants in the affordable speed tests, that we attribute to the engaging effect of virtual reality.

To summarize from the ideas drawn from the statistical analysis, the application of this tool should be limited to low or moderate speed exercise environments, excluding high speed applications from the scope of this system. Hence, these validation results have a clinical implication. In first place, our approach can be considered suitable as an engaging tool to practise cycling exercise, as it is assumed low-moderate pedalling speed for this group of users. It should also be considered the remarkable accomplishment of the VCP in the estimation of cycling cadence only based on hip ROM by only one inertial sensor. As a result, we developed a virtual cycling platform independent from the cycling ergometer or stationary bike used, which only requires the use of one inertial sensor and Oculus Quest 2 HMD.

The present study has been performed with young healthy subjects, whose hip range of motion (ROM) is wide. The joint motions obtained (Figs. 6, 7) during standardized ergometer cycling conform to the hip normal range of motion investigated by different authors (Ericson et al. 1988; De Roeck et al. 2021). According to their studies, in the case of healthy young people the hip flexion moves between 32° and 70° of hip flexion (Ericson et al. 1988), which implies a range of movement of approximately 40°. From the characterization of hip flexion motion performed in this study, slight differences in the maximum and minimum hip flexion angles as a function of speed can be observed. And yet, our solution is suitable for hip flexion-extension work in these normal ranges. However, it would be worth analysing the validity of the tool with elderly subjects or participants with motor disabilities to know if it also correctly detects cadence cycles with tight hip ROM. Futhermore, most studies analyse joint kinematics at a cadence of 60 rpm (Johnston 2007). In our study, we have analysed the cadences of 30 rpm, 60 rpm and 90 rpm, in order to analyse which range of cadence our application shows good accuracy in cadence estimation with respect to the system of reference. It is important to consider that our development is focused on the rehabilitation and improvement of lower limb mobility for adults, so they are not expected to work at high cadence. In this sense, our approach would be valid for the purpose for which it has been designed.

We highlight from our approach that it does not depend on specific cycling ergometers or hardware (Chen et al. 2017) since it estimates the cadence based on user's hip kinematics instead of crank angle of the ergometer likewise (Cardoso et al. 2019; Ferreira et al. 2019; Grani and Bruun-Pedersen 2017). The easiness and accessibility of the setup sets the universality of the system, yet being useful as virtual rehabilitation solution in day-care centres, rehabilitation clinics or even for home-based therapies. Also, in the near future, we plan to improve the design of the virtual scenarios to allow different uses of the tracking sensor, for example, to capture circular movements for the upper limb. Another positive aspect is that our approach is perfectly portable and simple to assemble, unlike the systems proposed by Cardoso et al. (2019), Ferreira et al. (2019) and Grani and Bruun-Pedersen (2017), which are based on the mechanical adaptation of commercial ergometers crank/pedals or custom hardware developments.

In terms of the sense of presence and immersion of our system, no formal survey has been conducted in this technical validation to capture these user ratings. However, in future usability testing and assessment of the potential effect of this platform, it will be essential to collect users' subjective assessments of their perception of immersion and presence. However, based on what was observed in the experimental tests, it should be mentioned that the participants were truly involved in the virtual reality as they showed their captivation during the exercises and even allowed themselves to be drawn into the environment, sometimes even causing slight variations in the maintenance of the cadence. We believe that this feedback strategy may not only be beneficial in increasing exercise adherence but also justifies the use of these technologies for this purpose. It differs from the strategies implemented in the exergames previously presented (Cardoso et al. 2019; Ferreira et al. 2019), which displayed the sensing data to the user with the purpose of enhancing their performance, but it does not necessarily have an effect on user's engagement nor motivation. For this reason, we endorse the philosophy of proprioceptive stimulation in VR as a strategy to involve the user in the physical activity followed in some studies (Grani and Bruun-Pedersen 2017; Guo et al. 2017; Caserman et al. 2019). All in all, we have designed a virtual reality system that maps the user's physical actions into virtual reality feedback and/or behaviour to provide consistency and verisimilitude to the virtual environment. We think this system could be potentially beneficial for increasing user engagement and motivation to use intrinsic biofeedback to influence the sense of presence within the virtual environment.

5 Conclusion

In this paper, a novel low-cost wireless standalone platform for VR-based cycling exercises is developed. This system is based on a wearable IMU sensor paired with the Oculus Quest 2 headset and a common stationary bicycle. The present development has focused on defining an optimal hip flexion motion detection algorithm for pedalling in the sagittal plane for a virtual reality environment. Further research is required to analyse more planes of movement, as the literature suggests performing a three-dimensional (3D) movement analysis instead of a two-dimensional analysis of an isolated plane. This would require to analyse the technical feasibility of increasing the computational load and how it affects the performance of the application, as the current processing of our system is fully done on an Oculus Quest 2 HMD.

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Declarations

Conflict of interest Raya R. is the CEO of Werium Solutions; Rojo A. is a software developer at Werium Solutions. The other authors declare no conflict of interest. The funding sponsors have no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript and in the decision to publish the result.

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CHAPTER 6: PEDALEOVR: USABILITY STUDY OF VIRTUAL REALITY APPLICATION FOR CYCLING EXERCISE IN PATIENTS WITH LOWER LIMB DISORDERS AND ELDERS

PedaleoVR: Usability study of a virtual reality application for cycling exercise in patients with lower limb disorders and elders

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Abstract

Achieving adherence to physical exercise training is essential in elders and adults with neurological disorders. Immersive technologies are seeing wide adoption among new neurorehabilitation therapies, as they provide a highly effective motivational and stimulating component. The aim of this study is to verify whether the developed virtual reality system for pedaling exercise is accepted and could be safety, useful and motivating for these populations. A feasibility study was conducted with patients with neuromotor disorders and elderly people from Lescer Clinic and the residential group Albertia, respectively. All the participants performed a pedaling exercise session with virtual reality platform. Then, the Intrinsic Motivation Inventory , the System Usability Scale (SUS), Credibility and Expectancy Questionnaire , were assessed in the group of 20 adults (mean age=61.1; standard deviation=12.617, 15 males and 5 females) with lower limb disorders . While the Simulator Sickness Questionnaire , Presence Questionnaire , Game user Experience Satisfaction Scale and SUS were assessed in the group of 18 elders (mean age=85.16; standard deviation=5.93, 5 males and 13 females). In light of the outcomes, PedaleoVR is considered to be a credible, usable and motivational tool towards adults with neuromotor disorders to perform cycling exercise, and therefore its usage could contribute to adherence to lower limb training activities. Moreover, PedaleoVR does not generate negative effects related to cybersickness while the sensation of presence and the degree of satisfaction generated have been positively evaluated by the geriatric population. This trial has been registered at ClinicalTrials.gov under the identifier: NCT05162040, Dec 2021

Introduction

The most frequent causes of sudden neurological injuries and lower limb disorders (LLD) are trauma and stroke [1]. Regarding the rehabilitation of locomotion after spinal cord injury or stroke, there has been considerable controversy and debate about the efficacy of the different approaches used [2]. New approaches propose an adaptation of therapy to the patients' motor learning process [3] [4] [5]. Although the referenced literature focuses on the rehabilitation of cerebrovascular patients, due to the extension of this field, the idea of adapting therapy to the motor learning process can be equally applied to patients with other neurological lesions in a way that therapeutic exercises are combined with stimulating environments.

According to the statistics of the Eurostat, "in 2019, more than one fifth (20.3%) of the European Union (EU) population was aged 65 and over" [6]. Moreover, the growing pace of elderly segment population is concerning, since the EU population over 80 years is projected to increase from 5.8% to 14.6% to 2100 [6]. As it is well-known, population undergoing an aging process eventually suffers a series of neurophysiological events that affect the loss of muscle mass, strength and balance control, causing falls in the elderly [7]. Often, those who suffer a fall must undergo long periods of rehabilitation to get full recovery, affecting their dependence in their daily lives. Indeed their functional situation has an impact on the quality of life of these patients [8]. With the determination to reduce the rate of falls, several scientific studies agree that physical exercise can help to attenuate the incidence of the so-called age-related conditions [9]. More effective interventions based-on personalized exercises for the patient and designing physical training programs can improve the muscle strength and balance, alleviating the decline in mobility in the elderly [10].

For both populations, patients with LLD and elderly people, a common interest is identified: the need for training tools to encourage physical activity to improve motor control, stability in gait function and lower limb strengthening. Regarding regular physical activity (PA) therapies for these populations, there are more and more PA interventions that propose pedaling activities, since the use of exercise bikes presents an affordable cost for patients and they are simple to use [11]. However, most of the programs that promote pedaling as a practice for physical strengthening do not offer real-time progress information to clinicians due to the lack of standard definition, follow-up protocols and quantifiable indices of functional improvement [12, 13]. On the other hand, in terms of emerging technologies applied to this area, immersive technologies stand out. Their potential lies in the ability to generate controlled and personalized immersive environments where the movements made by the patient can be captured and objectively quantified. Through immersive environments to the therapy makes potential motor learning a transparent process for the user. Moreover, modifying different sensory aspects of the learning environment can influence motor behavior [14]. In the course of therapeutic programs, adding simple sensory stimulation could improve sensory and motor function in neurological patients [15]. Latest studies have focused on demonstrating that stimuli environments-based physical training facilitates the recovery of motor function in neurological patients [16] [17]. Exergames technologies, such as Nintendo Wii™or Kinect™, are widely used to stimulate older adults in initiating or maintaining physical activity [18]. These technologies have had a rapid adoption in this field due to its low-cost, but also they are relatively simple to install and use [19] [20]. In addition, exergames with computers as well as virtual reality clearly provides a positive motivational aspect for physical activity [18] [20]. These rehabilitations based on immersive technologies increase patient motivation by allowing to perform physical activities in virtual environments (VEs), providing the patient feedback on the goals achieved. All these strategies are based on task repetition, which increases intensity and tension during exercise and facilitates motor learning and neuroplasticity [21].

To the authors' knowledge, even the use of these interactive technologies does not always guarantee better outcomes in PA by themselves, it can be assumed that they enhance adherence to training programs and physical activity, which has a positive effect on motor functioning on the older adults and patients with LLD. The importance of motivation itself in every physical field is undeniable, but in neurorehabilitation, the use of interactive technology and exergames-based system have proven to be effective to motivate persons with disabilities to perform exercise [22]. But whether the use of these technologies is fully accepted by this population more than other tools to perform physical exercise and how motivating are they perceived is being explored recently by some authors [22–24]. And their conclusions call for more evidence to support their tentative conclusions. The researchers of this study developed a novel virtual reality platform designed to achieve greater adherence to cycling exercise through the use of gamification strategies and user motivation [25] for adults with LLD and older adults. Due to these good results in the technical validations, the researchers understand that the developed tool will be used by the population of people with motor disorders if they find it motivating and useful for their rehabilitation process, while it will be used by the adult population if they positively tolerate this technology and are satisfied with its use. Thus, the researchers wish to validate the following hypotheses:

- Do patients with LLD see this virtual reality platform for pedaling as a positive value for their rehabilitation? Does the use of this virtual platform provide them with motivation for physical exercise pedaling?
  To address these questions we hope to gain information on credibility and intrinsic motivation ratings.
- Do adults accept virtual reality technology as a tool for pedaling physical activity? Are they satisfied with using this platform?
  To address these questions we expect to gain information on satisfaction, sense of presence, and user experience ratings.
- Do both populations find the platform design easy to use? To address this question we hope to validate the tool from a usability point of view.

In general, it is expected to validate the characteristics of virtual reality in this platform for the promotion of the approximate pedaling activity from two different populations that could find in its use a potential benefit. Then, in the present study, the differences between the two populations are known and respected by the authors. The intention is not to compare them but to evaluate how the same VR platform for the promotion of the pedalling activity can nurture relevant aspects of use for each population. Therefore, the data from each case are shown separately throughout the Results and Discussion sections.

Materials and methods

Participants

The participant screening protocol was based on the following inclusion and exclusion criteria applied by the physicians of the Lescer Clinic and Albertia. Inclusion criteria were: (1) individuals were eligible if they had been prescribed pedalling exercise as treatment for lower limb training or rehabilitation (2) They also had to be able to perform a pedalling session with virtual reality technology.

Exclusion criteria were: (1) an insufficient cognitive state, in particular, presence of dementia or mild cognitive impairment; (2) an unbound bone fracture; (3) severe disorders of vision and/or audition (inability to perceive visual and/or auditory information coming from virtual reality); (4) whose clinical record ruled out any incompatibility with the use of a virtual reality system.

The CONSORT diagram (Fig 1) shows the participant flow through the study, including enrollment, experimental intervention and analysis. As it is depicted in Fig 1, finally eighteen elder participants from Albertia met these criteria (5 males and 13 females, mean aged= 85.16 (standard deviation=5.93)) and provided written consent to be enrolled onto the study. Likewise, 21 participants from Lescer Clinic met these criteria and provided written informed consent to be enrolled onto the study, but only 20 participants completed the study (15 males and 5 females, mean aged=61.10 (standard deviation=12.62)). Participants with neurological pathologies were diagnosed with (6) ischemic strokes, (1) hemorrhagic stroke, (1) thalamic stroke, (1) internal capsule stroke (3) traumatic brain injury (TBI), (1) Parkinson syndrome, (1) mixed axonal neuropathy with sensory demyelination, (1) progressive multifocal leukoencephalopathy, (1) secondary obstructive hydrocephalus, (1) angioma avernosus hemorrhage, (1) hemiprotuberancial hemorrhage - cavernoma, (1) ataxia and (1) cerebral artery aneurysm. The clinical conditions, gender and age of the participants are shown in Table 1.

Table 1. Socio-demographic and clinical characteristics of patients from Lescer Clinic by gender, age and clinical condition.

Gender	Age	Clinical Condition
M	59	Hemorrhagic stroke
M	39	Thalamic stroke
M	75	Traumatic brain injury
M	45	Cerebral artery aneurysm
F	71	Ischemic stroke
M	57	Ischemic stroke
F	88	Ataxia
M	71	Internal capsule stroke
M	39	Severe traumatic brain injury
M	62	Ischemic internal carotid stroke
M	77	Axonal mixed neuropathy with sensory demyelination
F	64	Angioma avernosus hemorrhage
M	53	Ischemic stroke
M	53	Ischemic stroke
M	62	Ischemic stroke
M	58	Hemiprotuberancial hemorrhage - cavernoma
F	72	Traumatic brain injury
M	56	Progressive multifocal leukoencephalopathy
M	72	Parkinson syndrome
F	49	Ischemic stroke

Procedure

All the participants gave written informed consent, in accordance with the Research Ethics Committee of Universidad CEU San Pablo (approval code: 550/21/51). Additionally, the protocol of the study was registered at Clinicaltrials.gov with reference: NCT05162040. The privacy rights of human participants were observed at all times.

Prior to starting the pilot and completing the questionnaires, written informed consent was obtained, and the participants read instructions of the questionnaires.

First, a practical explanation of familiarization with the instrumentation is carried

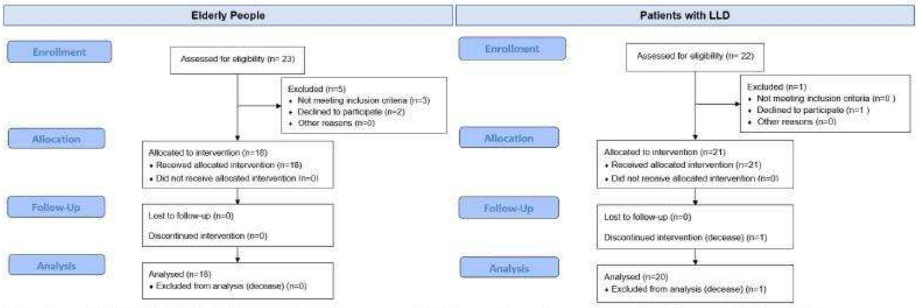

Fig 1. CONSORT flow diagrams of the elderly people from Albertia Servicios Sociosanitarios and patients with lower limb disorders from Lescer Clinic.

out, aimed at acquiring basic skills in the use of the virtual reality environment synchronized with the pedaling task. The 'Landscape Flight' scenario was used for the familiarization trial since it is the most peaceful VE of all three and it has fewer distracting elements. Then, a pedaling exercise is performed on a static pedaling ergometer synchronizing the physical activity with the visual feedback of the virtual reality application. Two pedaling sets of 5 minutes each are performed, with 1 minute rest between sets. All the participants underwent both sets of pedalling with the 'High Flight' VE. This scenario infuses greater sensation of dynamism due to the displacement of the clouds, the speed of the plane's movement and the speed of the propeller. Moreover, the appearance of animated elements such as birds, other planes and fog banks, along the route, are elements that can captivate the user's attention, increasing their sense of presence. Once the exercise task was completed, several questionnaires were administered by a researcher to evaluate the experience of the patients with LLD and the elderly participants with PedaleoVR. In the case of the elderly, the cybersickness survey was taken before and after the use of PedaleoVR. All responses of all the questionnaires were subsequently digitized and the paper questionnaires filed.

Virtual Reality Cycling Platform

A lower extremity motor training platform has been developed for adult patients with impaired control due to neurological damage and older adults using an immersive virtual reality system that establishes a progressive and individualized training program based on the rehabilitation of gait function.

PedaleoVR implements extrinsic feedback strategies, gamification by levels, and personalising of the sessions with the aim of achieving greater adherence to the users' pedaling exercise sessions. Its immersive nature means an increase in the feeling of "presence", generating an impact on the subject's involvement in achieving the training objectives.

Description of the VR Platform: PedaleoVR

PedaleoVR consists of two parts: a sensing system which integrates micro-controller unit (MCU), inertial measurement unit (IMU) and a Bluetooth module, and a virtual rehabilitation training scene, as shown in Fig 3. This VR system is based on the communication of pedaling data and surrounding information to the control computer. The data transmission from the inertial sensors to the Oculus Quest 2 head-mounted display (HMD) is established via Bluetooth. The VR platform supports the data

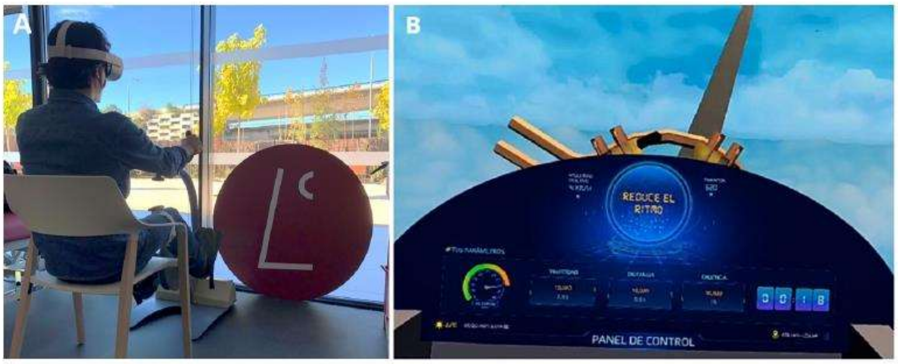

Fig 2. Pilot session with subjects with neuromotor disorders. (A) Participant using the virtual cycling platform. (B) Capture of the first-person view of the virtual scenario 'High Flight'.

processing of pedaling cycles, speed and distance traveled of each user and the transmission of these values to the immersive scenarios.

The motion capture system for pedal kinematic analysis to be used is the ENLAZA™ sensor from Werium Assistive Solutions, due to the proven reliability of its ROM measurements at the cervical [26], wrist and elbow joints [27]. The ENLAZA™ sensor module contains an inertial measurement unit (IMU) with 9 degrees of freedom, which integrates a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer. The sensor also includes a Bluetooth module (2.4 GHz) through which the IMU data is sent to the virtual reality device.

Virtual Scenarios

The PedaleoVR was developed using Unity3D Game Engine software. In total, 3 virtual games were developed. These VR scenarios generated for this therapy consists of controlling the forward movement of a vehicle by pedaling. Thus, the user is placed inside the vehicle's cabin and visualizes the session data on the control panel (Fig.2).

The whole virtual platform consists of two main spaces. Firstly, there is a standby area where the user logs in him/her-self in the system, his/her ranking records are displayed and he/she can select the game ambience where to perform the pedalling session. The next space of this experience consists of the three games with different ambience scenery (see Fig.3). (i) **Game High Flight**: the navigation vehicle is a light aircraft and the flight environment is the sky; (ii) **Game Landscape Flight**: the navigation vehicle is a light aircraft and the flight environment is a canyon valley; (iii) **Game Sailing Night**: the navigation vehicle is a fishing vessel and the sailing environment is the sea.

Visual Biofeedback

The system implemented in the VR platform evaluates every second the average pedaling speed of the last 3 seconds with respect to the target speed. A threshold of acceptance of the instantaneous speed is set at ±15% of the target speed. Higher values are considered too fast and lower values too slow, so pop-up messages are generated to moderate or increase the pedaling cadence accordingly. Motivational messages are displayed when the user maintains an adequate pace.

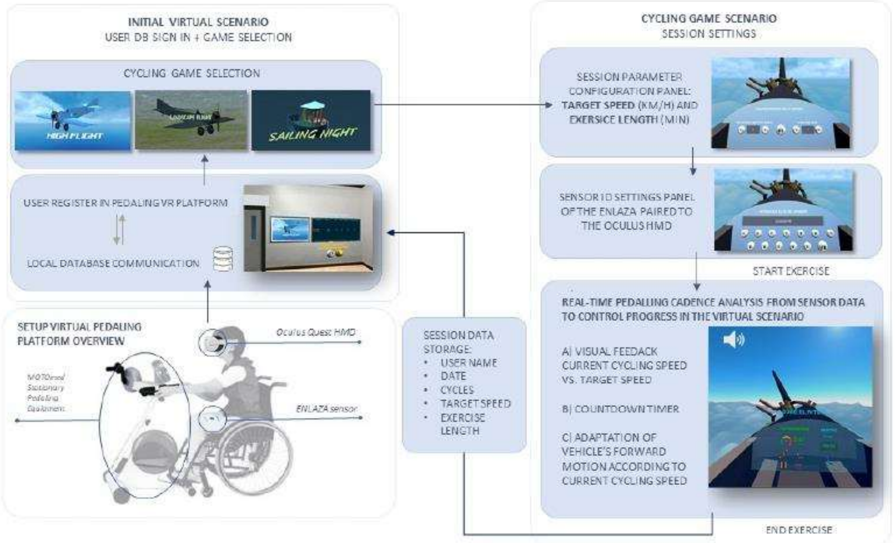

Fig 3. Workflow diagram of the Pedaling Virtual Platform user experience.

Measurements

All assessments were performed by the researchers of the study. The following 6 questionnaires were used for the corresponding assessments of each group of participants, neurological patients and elderly people.

Intrinsic Motivation Inventory. The IMI is considered a reliable assessment (intraclass correlation = 0.70) and was selected to evaluate the motivation to use the PedaleoVR. It assesses the participant's subjective experience related to a target activity in laboratory experiments, in this case the PedaleoVR exercises. The instrument assesses participants interest/enjoyment, perceived competence, effort, value/usefulness, felt pressure and tension, and perceived choice while performing a given activity, thus yielding six subscale scores. The IMI items have often been modified slightly to fit specific activities. Nonetheless, shorter versions have been used and been found to be quite reliable. The present study used the IMI 25-item version which includes the three subscales of value/usefulness, interest/enjoyment, and perceived choice. A total IMI score is not recommended, therefore subscale scores, each with a recalculated maximum score of 7, are used in the analyses [28].

Credibility and Expectancy Questionnaire, CEQ. The CEQ was selected to evaluate the credibility and expectancy with regard to the PedaleoVR for improvement of PA and is also considered a reliable assessment (Cronbach's alpha = 0.85). The Credibility/Expectancy Questionnaire is the most widely used measure of treatment credibility and expectancy in psychotherapy research. It contains 6 items rated on a 1-9 or a 0%-100% scale, depending upon the item. This revised scale, which was used in the present study, has been subjected to factor analysis, with results indicating that the items load onto two distinct factors of credibility and expectancy. The first three items of the scale load onto the credibility factor and the final three items load onto the expectancy factor. The maximum score on each subscale is 27. A score of 13.5 is considered neutral, everything above 13.5 is positive while everything under 13.5 is considered negative [29].

Simulator Sickness Questionnaire, SSQ. The SSQ is widely used in VR research to assess users' level of sickness symptoms based on subjective severity ratings of 16 symptoms on a scale from 0 (no perception) to 3 (severe perception) after the exposure [30]. The ratings for individual symptoms are divided into three non-exclusive categories that represent symptoms of nausea (N), oculomotor disturbance (O), and disorientation (D). The formulas dictate that the sum of nausea, oculomotor disturbance and disorientation, are multiply by the scaling factors 9.54, 7.58 and 13.92, respectively [30]. While the total simulator sickness score (TS) is computed by multiplying the sum of each category by the scaling factor 3.74. Therefore, a SSQ total scores above 20 is considered "bad" [31]. Similar thresholds can be assumed for the sub-scales nausea, oculomotor disturbance, and disorientation as the scaling factors were chosen to produce scales with similar variations [30].

Presence Questionnaire, PQ. VR studies commonly use the Witmer and Singer (1998) Presence Questionnaire (PQ) [32]. We used PQ Vs. 3.0, Nov. 1994, revised by UQO Cybersecurity Lab in 2004 which has been widely tested for reliability. PQ includes 24 questions that measure factors such as realism, control, quality of interface, possibility to examine, possibility to act, self-evaluation, sounds and haptic. Since in our study was not possible to manipulate objects with and did not include sounds, the optional sound and haptic questions were excluded, resulting in a 19-questions survey. Each question is evaluated on a 7-point Likert scale.

Game User Experience Satisfaction Scale, GUESS. To assess the satisfaction of gamified virtual application, we used the 18-item short scale of the Game User Experience Satisfaction Scale (GUESS-18) [33]. This questionnaire is a brief, practical, and comprehensive measure of video game satisfaction for practitioners and researchers, which is recommended to use in iterative game design, testing, and research. The GUESS-18 scale consists of nine subscales: usability/playability, narratives, play engrossment, enjoyment, creative freedom, audio aesthetics, personal gratification, social connectivity, and visual aesthetics. The GUESS-18 items are rated with a 7-point Likert scale (1 = Strongly Disagree to 7 = Strongly Agree). Calculating the subscales scores of the GUESS-18 consists of averaging the items in that subscale and an overall score calculated by summing the subscale scores.

System Usability Scale, SUS. The SUS test has become an industry standard as it allows to evaluate a wide variety of products and services, including hardware, software, mobile devices, websites and applications. Whereby, the SUS was selected to evaluate the usability of PedaleoVR within adults and is also considered a reliable assessment (Cronbach's alpha = 0.91). The item scores on the SUS range from 1 (totally disagree) to 5 (totally agree) and are converted into a score from 0 (negative) to 100 (positive). A score of 72.5 or higher is considered good and above 85.0 is excellent [34].

Statistical Analysis

To determine the sample size for these feasibility studies of PedaleoVR in different populations, we set the following hypothesis: We want to identify whether these issues (usability, credibility, intrinsic motivation, sense of presence, VR sickness and satisfaction) affect 10% or more of our participants with an 85% probability of detecting them in a feasibility test. With these requirements, we need to recruit at least 18 participants, which is estimated from the formula: log(1-.85) / log(1-.10) = 18.006. Therefore, the samples of 18 and 20 participants were presumed appropriate to capture heterogeneous data for analysis. In this paper, means and standard deviations were calculated for each of the metrics. These parameters allow us to statistically describe the aspects of credibility, expectation, intrinsic motivation and usability for the population of patients with LLD, and the aspects of satisfaction, sense of presence, generation of adverse aspects and usability for the population of older adults. Descriptive analysis of the questionnaire results and graphic plots were computed and generated with IBM SPSS Statistics (version 27.0).

Results

Table 2 includes the descriptive analysis of the IMI, CEQ and SUS questionnaire responses of patients with LLD. IMI mean values of each subscale are shown in Fig 4, and CEQ mean values of each subscale are shown in Fig. 5. The results of cybersickness questionnaire of older adults are included in Table 3 and the cybersickness ratings of the previous-exposure and post-exposure are shown in Fig 6. Table 4 includes the outcomes of presence, satisfaction and usability of older adults. Regarding the PQ outcomes, the mean values obtained in each subscale are shown normalized in Fig 7. GUESS-18 mean values of each subscale are shown in Fig 8. And the SUS outcomes for both groups are shown in Fig 9.

Case Study 1: Patients with LLD

Table 2. Mean and standard deviation (SD) outcomes of Intrinsic Motivation Inventory (IMI), Credibility/Expectancy Questionnarie (CEQ) and System Usability Scale (SUS) of patients with neuromotor disorders. The interpretation of the mean scores for each subscale is provided in the form: U = unacceptable outcome; A = acceptable outcome; HD = highly desirable outcome.

Assessment	**Mean (SD) (n=20)**	**Score interpretation**
IMI		
Interest/Enjoyment	4.593 (1.363)	U= 0-3; A= 3-5; HD= 5-7
Value/Usefulness	4.783 (1.555)	U= 0-3; A= 3-5; HD= 5-7
Perceived Choice	5.281 (0.843)	U= 0-3; A= 3-5; HD= 5-7
CEQ		
Credibility	18.300 (5.595)	U= 0-13; A= 13-20; HD= 20-27
Expectancy	15.050 (6.004)	U= 0-13; A= 13-20; HD= 20-27
SUS	80.3754 (15.558)	U= 0-50; A= 50-72.5; HD= 72.5-100

Intrinsic Motivation

The mean value of "interest/enjoyment" subscale (4.593/7.000) is the lowest outcome of all three categories. Despite this result, it is still consider a really good outcome as it indicates that the participants are motivated by PedaleoVR to perform the cycling exercises. While VE and the game is enjoyable, it is understandable to reach monotony at some point during cycling activity, which could affect on the interest aspect. Acknowledging this issue, it may be considered for future iterations of the prototype to include other motor activities that are stimulating for the subject.

The mean value of "value/uselfulness" subscale (4.783/7.000) indicates that the participants perceived PedaleoVR as a useful and valuable tool for their motor functioning recovery. It is also noticed that in some cases participants have given low ratings to the platform, these ratings are attributed to some people's distrust of these technologies and their lack of habit of using them. But this samples are the less.

Credibility/Expectancy

Credibility is associated with logical thinking while expectation is associated with an effective process. Then, the following ideas can be extracted from the results of the Credibility/Expectancy Questionnaire: In terms of credibility, they believe that performing cycling exercise with PedaleoVR can support them in their rehabilitation(18.300 ± 5.595). Besides that, the participants have moderate expectancy

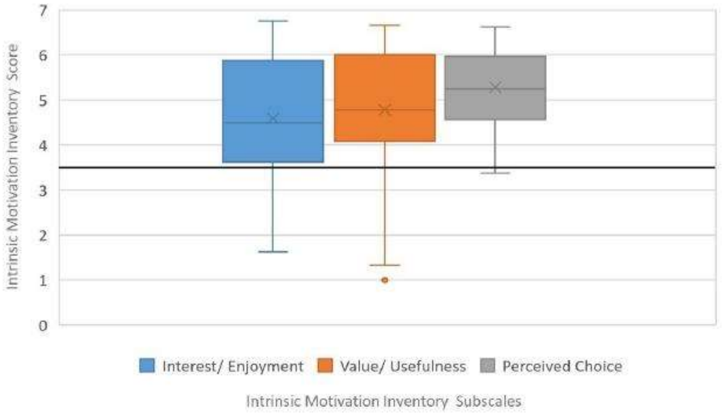

Fig 4. Boxplot distribution of IMI assessment: Interest/Enjoyment, Value/Usefulness, Perceived Choice.

(15.050 ± 6.004) that they will improve in their physical functioning by exercising with PedaleoVR.

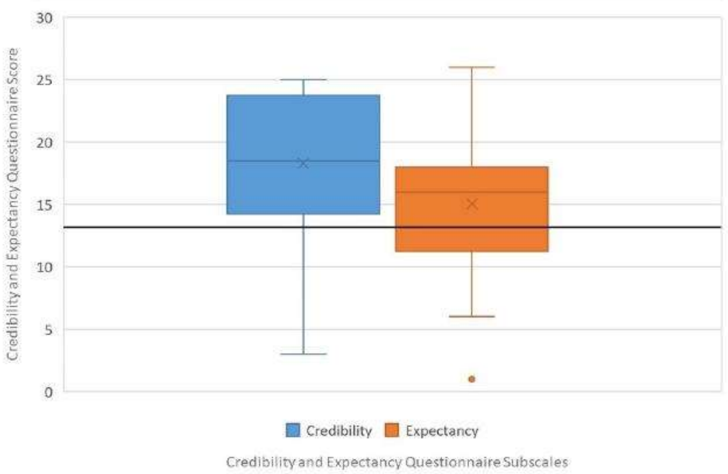

Fig 5. Boxplot distribution CEQ assessment: Credibility and Expectancy.

Case Study 2: Elderly people.

Simulator Sickness Questionnaire

SSQ-scores were calculated based on official guidelines [30]. Considering the post-test SSQ results, the scale associated with disorientation had the lowest score (6.186 ± 11.574) followed by the nausea symptomatology scale (7.420 ± 14.062) and finally the oculomotor symptoms scale (8.422 ± 13.343). In general, following aforemention interpretation [31], none of the subscales exceeds 20 points, so it could be said that the VR cycling platform does not cause negative effects. Nevertheless, a recent study [35] suggested administrating the SSQ both before and after the exposure of an

Table 3. Mean and standard deviation (SD) outcomes of Simulator Sickness Questionnarie (SSQ) Pre-experimental test and post-experimental test, and differential values of elderly people. The interpretation of the mean scores for each subscale is provided in the form: N=negligible; M=minimal; S= significant; C = concerning; U = undesirable.

Assessment	Mean (SD) (n=18)	Score interpretation
Pre-test SSQ	3.710 (5.797)	
Nausea	3.710 (5.797)	N< 5; M=5-10; S= 10-15; C= 15-20; U> 20
Oculomotor	4.632 (6.946)	
Disorientation	2.320 (5.338)	
Post-test SSQ	7.420 (14.062)	
Nausea	7.420 (14.062)	N< 5; M=5-10; S= 10-15; C= 15-20; U> 20
Oculomotor	8.422 (13.343)	
Disorientation	6.186 (11.574)	
Difference	4.363 (9.350)	
Nausea	3.710 (9.613)	N< 5; M=5-10; S= 10-15; C= 15-20; U> 20
Oculomotor	3.79 (8.089)	
Disorientation	3.866 (9.051)	

experimental condition. Thus, it seemed reasonable to take a baseline to offer more specific insight into the effects of the use of the VR cycling platform by subtracting the values of the previously presented symptoms. After calculating the differences between the pre-test and post-test SSQ, the values of each subscale are still lower (see Table 3). This reinforces the conclusion that the VR cycling platform has no negative effects on elderly people. These results are favourable because it is undesirable to generate adverse effects in the aging population.

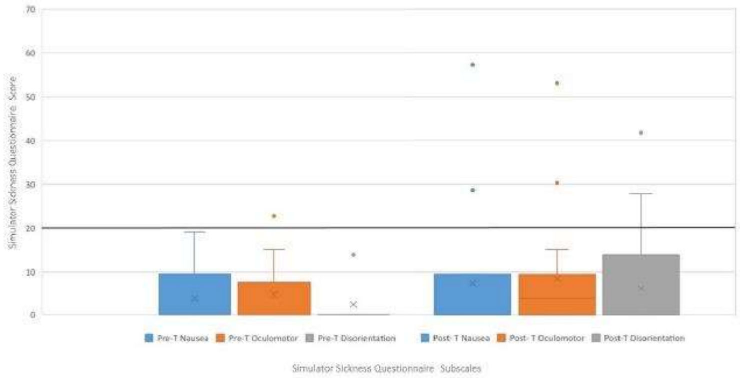

Fig 6. Boxplot distribution of Pre-Post SSQ assessment.

Presence Questionnaire

Regarding the overall QT Score of the patients, a total mean of 71.000/108.000 was obtained with a standard deviation of 23.225. The moderately high score indicates that users are generally satisfied with the VE but it could have been better. This assessment is consistent with the design characteristics of the application, which does not exploit all the auditory and haptic stimulation resources or all the interactive options, which could increase user' sense of presence. In order to compare the outcomes (see Table 4) of the

Table 4. Mean and standard deviation (SD) outcomes of Presence Questionnaire (PQ), Satisfaction Questionnaire (GUESS-18) and System usability Scale (SUS) of elderly people. The interpretation of the mean scores for each subscale is provided in the form: U = unacceptable outcome; A = acceptable outcome; HD = highly desirable outcome.

Assessment	**Mean (SD) (n=18)**	**Normalized mean**	**Score interpretation**
PQ			
Realism	29.375 (12.750)	0.699	U= 0-0.5; A= 0.5-0.75; HD= 0.75-1
Possibility to act	12.750 (7.554)	0.531	
Quality of interface	2.500 (2.329)	0.791	
Possibility to examine	11.250 (3.991)	0.625	
Self-evaluation	8.125 (1.807)	0.677	
GUESS-18			
Usability	6.625 (0.763)	-	U= 0-3; A= 3-5; HD= 5-7
Narratives	6.406 (0.898)	-	
Play Engrossment	6.218 (1.095)	-	
Enjoyment	5.471 (1.815)	-	
Creative Freedom	5.5004 (1.879)	-	
Audio Aesthetics	5.8214 (1.749)	-	
Personal Gratification	6.937 (0.250)	-	
Social Connectivity	5.500 (1.949)	-	
Visual Aesthetics	6.781 (0.546)	-	
SUS	68.472 (18.145)	-	U= 0-50; A= 50-72.5; HD= 72.5-100

different subscales with each other, the values have been normalized and represented in a radar plot (Fig 7. Thus, it can be seen that the subscales with the highest mean are the ones corresponding to the quality of the interface with 0.792/1.000 and the realism with 0.701/1.000. While the lowest means subscales are the possibility of acting, with 0.5312/1.000, the possibility to examine with 0.625/1.000, and the self-evaluation performance with 0.677/1.000. Additionally, from the analysis of the raw data, a high correlation was observed between the realism subscale and the ability to act subscale. From this finding, it can be deduced that the visual enhancement of the VR platform with photorealistic graphics could in turn improve the user's perceived ability to act. Finally, lower values on the scales of possibility to examine and possibility to act are reasonable, as the environment designed for the play objectives of the pedalling activity did not support these possibilities.

Game User Experience Satisfaction Scale

Regarding the overall GUESS -18 Score of the patients, Table 3 shows the average of all subscales where the highest values correspond to the subscales of Personal Gratification ($6.937/7.000 \pm 0.250$), Visual Aesthethics($6.781/7.000 \pm 0.546$), Usability ($6.625/7.000 \pm 0.763$), Narratives ($6.406/7.000 \pm 0.898$) and Play Engrossment ($6.218/7.000 \pm 1.095$). On the other hand, the lowest mean values correspond to the subscales of Enjoyment ($5.471/7.000 \pm 1.815$), Creative Freedom ($5.500/7.000 \pm 1.815$), Social Connectivity ($5.500/7.000 \pm 1.949$) and Audio Aesthetics ($5.821/7.000 \pm 1.749$). The score on the Social Connectivity subscale is particularly noteworthy, as although it is understood that this application has the potential to scale to a multiplayer system and that the social interaction [36, 37] could be an incentive for users. But, drawn from the results, the Social Connectivity aspect does not seem to have been considered

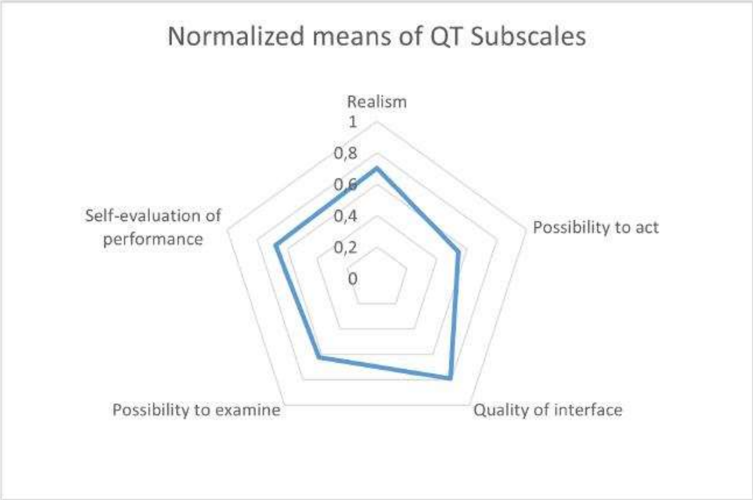

Fig 7. Radar plot of normalized means of PQ subscales assessment.

relevant by the elderly people themselves. Although the result of the Enjoyment subscale is positive and moderately high, it can also be interpreted in a similar way to the values of the intrinsic motivation subscale carried out with patients with LLD. Since the elderly are also aware and knowledgeable of the benefits of physical activity, it can be considered that the satisfaction reflected also encompasses this self-motivation and the values of the enjoyment subscale hint at this fact. The overall score for all patients is 51.647 over 63, which confirms that participants were very satisfied with the system used. In general, the ratings are consistent with the design of VR cycling platform.

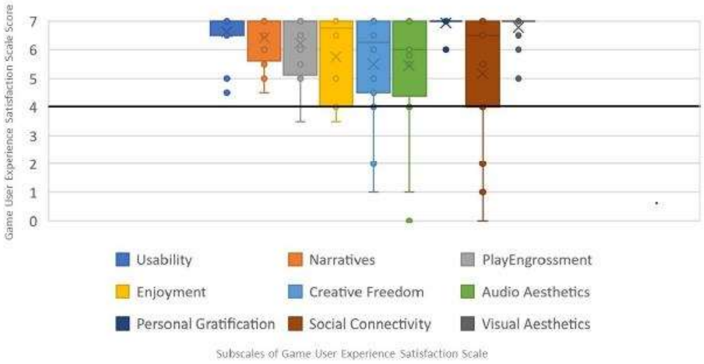

Fig 8. Boxplot distribution of GUESS-18 subscales.

Usability and feasibility

The results of the SUS from patients with LLD (80.375 ± 15.558) suggest that the ease of use of PedaleoVR is very good. These results were to be expected since the participants had no problems handling the VE. This success is attributed in part to having dedicated an explanation and familiarization phase with the technology prior to the test. Knowing the average age of the participants and predicting their lack of experience with virtual reality technologies, it was deemed necessary to include this previous step in the experimental protocol. This measure did not seem to be sufficient in the case of the elder participants, who did not always show full confidence in the system through the experimental tests, and as a result, the SUS score obtained was almost 12 points lower (68.472 ± 18.145).Even so, both usability ratings were good, if not better in the case of the younger adult group. On the other hand, an interface design was generated that was consistent with the needs of this group of adults. Also, the whole system should be simple and easy to use, it should not generate movement constraints for the patient during pedaling exercise.

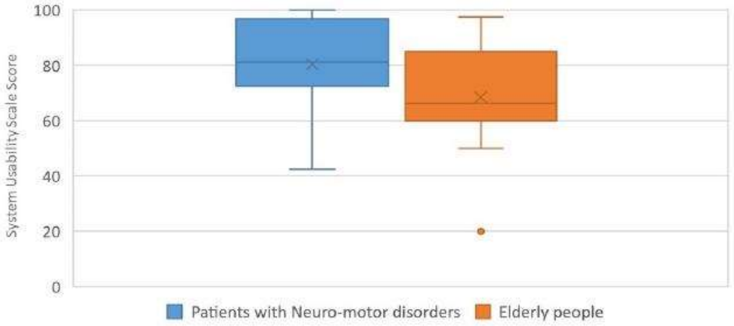

Fig 9. Boxplot distribution of SUS assessment of both groups.

Discussion

The present study aimed first to analyze the usability of the virtual cycling platform by two different population groups with lower limb motor disorders. Secondly, the study sought to answer the prevously stated hypothesis. The results extracted from the standardized questionnaires of each case study (group) are here discussed and summarized.

The IMI questionnaire reflects the subjective experience of the participant with regard to a target activity. This instrument allows the measurement of different aspects of a person's motivation. Measuring how a system or technology is perceived interms of usefulness is a way to valid and to predict the technology use, intentions and attitudes towards working with that system, according to Chen et al [38]. For these reasons, it can be said that this system is positively perceived and valued by adult patients with neuromotor disorders and their acceptance can be presumed. Related to the "Perceived choice" subscale of the IMI (5.281/7.000), the vast majority of them felt likely to perform the cycling activity. This positive predisposition to perform the activity is a key step in the maintenance of physical exercise.

From another point of view, some authors warn that while the IMI questionnaire is able to assess the intensity of motivation, it fails to identify the motivational dimension (intrinsic or extrinsic) [39]. As an example, in the context of PA, participants may indicate that they have enjoyed the activity, not because of the satisfaction of doing the activity per se, but rather because of the extrinsic rewards associated with participation [24, 40]. Translating this concern to our study, it is understood that patients with neurological disorders who attend rehabilitation already have an underlying extrinsic motivation for recovery. Thus, it could be expected that the assessments they make are mainly due to an intrinsic motivation generated by the virtual platform.

However, determining the level to which patients attribute their improvement to the usage of the VR platform can be assess by the CEQ. Regarding the CEQ insights, we can assume that adult neurological patients with LLD are convinced that PedaleoVR is a useful tool that can help them to perform physical activity, but they still need more convincing evidence that PedaleoVR can improve their physical functioning. This could be done by conducting a longitudinal study in which the impact of maintaining over the time the use of PedaleoVR on lower limb motor recovery is observed. Furthermore, providing more information about the positive benefits of performing pedaling activities in improving stability and gait function could improve their expectations. However, it is understood that depending on the severity of the patients' diagnosis, their expectations of physical improvement are moderate.

Additionally, the satisfaction questionnaire allows to measure the enjoyment of the person during an activity. The results of the Enjoyment or Person Interest subscale of the IMI reported by the LLD patients show values concordant with the results of the Play Engrossment, Enjoyment and Personal Gratification subscales of the GUESS-18 reported by the older adults. On the other hand, the usefulness and value scale of the IMI questionnaire provides information consistent with the credibility subscale of the CEQ. Both subscales reflect the extent to which the participant perceives the use of this tool to be beneficial. Both scales obtained acceptable values.

The sense of presence is an aspect that can significantly influence user motivation. In these terms, the categories of realism and interface quality are the most highly rated. Similarly, the visual aesthetics category of the GUESS-18 questionnaire is highly rated. In fact, all subscales of GUESS-18 scored on average between 5.4 and 7 points. These highly desirable values reveal the high user satisfaction with the platform. Although the results of the motivation, credibility and satisfaction scale show that users find the use of this platform rewarding, motivating, interesting and potentially valuable, it is necessary to re-evaluate the effect of this motivation in the long term. For there may be a novelty factor that alters this perception of motivation and therefore the actual engagement may decline over repeated use. This has also been noted in other similar studies [24].

In general, all Nausea, Oculomotor and Disorientation subscales of SSQ scored below 10 points, considering the adverse effects to be minimal. Even though, the value of each subscale is also shown in Table 3 as the difference in scores between the pre-exposure and post-exposure measures and, in this case, the values are negligible. Compared to other studies [23,24], the adverse effects measured are lower than those measured by previous studies. This may be attributed to the fact that the aesthetics of the virtual environment and the design of the platform are more sensitive to avoiding general user discomfort. Regarding usability, both populations have been explicitly consulted about this aspect of the platform. It can be concluded that for the adult population (whose mean age is 85.16 with standard deviation = 5.93) the ease of use is rated as adequate, while the population of patients with LLD (whose mean age is 61.10 with standard deviation = 12.62) rates the ease of use of the platform as excellent. We can conclude that both populations rated the usability of the platform positively, with a higher rating from the adult population with LLD.

PedaleoVR design aspects

It was essential to achieve a prototype that was consistent with these two characteristics. First, in order to make it easy to handle for these patients, whose neurological damage could also affect the upper limb, the use of VR controllers was dismissed. In line with improvements in hand recognition software, which is increasingly being used in the field of rehabilitation applications [41], we implemented and hand-tracking-based interactions with the VE. Second, the use of inertial sensors for controlling exergames has become used the most in virtual training tools [42] [43] as they are getting cheaper, their accuracy is increasing and gesture recognition is improving [44]. In addition to these reasons, the ENLAZA™ sensor is included, with the primary intention of incorporating a non-obstructive pedal movement capture system during pedaling that is adaptable for all patients and all stationary pedaling stations.As a result, it can be stated for the usability assessment of PedaleoVR, that it is perfectly feasible and easy to use tool for elderly people and patients with LLD.

Methodological aspects

As the present research is a usability and feasibility study, only descriptive statistics can be performed. For these reason, our results have to be handle with the upmost care. Findings of this study provide a context for the use of PedaleoVR in two different populations, and describe how the usage this novel system is perceived and accepted. However, analyzing the success of PedaleoVR as a tool to enhance pedaling exercise and its effects in adult patients with LLD requires further studies, as well as its potential effects in lower limb strengthen in elderly people. Nevertheless, the motivation and satisfaction outcomes agree with the reviewed studies which showed that exergames intervention groups were more motivated to exercise [45] and found the training more appealing than traditional exercises [46].

Limitations

This study has several limitations. First, given the descriptive nature of the study, we did not consider the current routine therapies performed by the participants. Therefore, it is possible that participants had different physical activity baselines, different habits of using technological tools, and different expectations regarding the platform presented.

Secondly, in the group of neurological patients, we can differentiate between a group of younger participants around 50 years of age and another group of older participants around 70 years of age. In the case of the group of older people, we find a group around 85 years of age. If we could have had a larger sample of participants in both cases, all the metrics could be analysed according to different age groups. However, due to this limitation, it has not been possible to carry out this characterisation, with the exception of SUS outcomes, where differences have been observed between the two groups, which presumably could be due to the difference in age and familiarity with the technology.

As a final observation, it is also worth considering that, pedaling exercise can be exhausting for those participants who are not in suitable physical condition to undertake the effort. This issue can compromise the enjoyment of the pedaling activity. Therefore, having a pedaling assistance system could be useful for these patients to avoid generating an initial demotivating due to lack of adaptation of the system.

Conclusion

Our research describes the core aspects of a virtual reality platform based on a standalone system for the promotion of pedalling activity in an immersive environment. The findings allow us to address enhancements and future designs of VE for older adults and patients with LLD. In overall conclusion, all participants agreed on great aesthetics of the VE and the VR platform design in terms of usability. These aspects could promote the enjoyment of the activity and personal gratification, which would also be contributing to the participant's motivation. Moreover, it has also been verified that the platform does not generate adverse effects due to the cybersickness of virtual reality in static activities. This evaluation has been carried out in an adult population and no cases of rejection of the technology for these reasons have been reported. Finally, further studies should explore the extent to which intrinsic motivation is maintained in the long-term. As a future direction it is considered that the addition of sound feedback, as well as performance scoring, may improve the user experience and, consistently, the engagement in exercise.

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Availability of data and materials

The datasets used and/or analysed during the current study are available at Zenodo Repository: 10.5281/zenodo.6882978. The protocol of the study is registered at Clinicaltrials.gov with reference: NCT05162040. Protocol documentation is fully available at Open Science Framework repository: DOI 10.17605/OSF.IO/93QFY

Competing interests

The authors declare that they have no competing interests.

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CHAPTER 7: SUMMARY, CONCLUSIONS AND FUTURE WORK

7.1. Summary

In the last 20 to 30 years immersive technologies are seeing wide adoption among new physical rehabilitation therapies, as they provide a highly effective motivational and stimulating component. Also, their entertainment capacity creates a sense of immersion in the users, which enhances adherence to their use. In addition, offering body-related visual feedback is a proven approach to the physical training towards a goal. These are the main reasons why VR applications on home-base exercise therapies have boomed in the last decade.

The literature reviewed in section 1.1.2. Rehabilitation for motor disabilities showed that the exercise of pedalling has the potential to provide a high number of flexion and extension repetitions of the lower limb in reasonable therapeutic time periods to improve muscle activity, strength, and balance in elders, but also motor improvements in patients with neurological injuries. However, the use of these interactive technologies per se does not imply greater effectiveness in physical improvement, but rather that adherence and continuity in treatment will have a positive effect on the motor functioning of older adults and patients with LLD. Although the importance of motivation in all physical domains is undeniable, few systems are available that exploit these benefits of fully immersive VR in pedalling activity, considering the scarce scientific literature.

This project contributes scientifically with the results of two studies that fully describe the safety, usability, satisfaction, intrinsic motivation, technology acceptance and sense of presence of the VR tool by two different target populations. It is presumed that the conclusions drawn from this research will enrich the body of knowledge described in section 1.3.2. Lower limb solutions for gait function and cycling in virtual reality. Furthermore, a technical feasibility study of the VR platform has been provided. Our VR platform is based on a commercial off-the-shelf VR HMD, a low-cost IMU sensor and any pedalling equipment, which sets it apart from existing systems in terms of technology. All the results obtained in the studies carried out within this thesis have been performed in a clinical setting.

In fact, the first milestone in the development of this platform was the integration of the ENLAZA^{TM} inertial sensor in a VE as a high precision motion tracker in VR. This integration would allow to capture motion of upper and lower limbs, depending on the needs. Therefore, our first approach was built with an inertial sensor, a Raspberry^{TM} Pi based computer and an Oculus Quest 2 device, following the schema shown in Figure 7. This first prototype allowed the Oculus Quest to receive via WiFi (through UDP protocol) the rotations captured by the linked sensor, thanks to a CPU that mediated the communication. This processing unit was a Raspberry^{TM} Pi to which the ENLAZA^{TM} sensor was paired via Bluetooth, and which computed the Euler angles from the direction cosine matrix transmitted by the sensor. The technical characteristics of this first prototype were studied in terms of measurement accuracy, reliability, and latency. According to the obtained results, it was concluded that this solution was comparable to state-of-the-art pose-tracking systems.

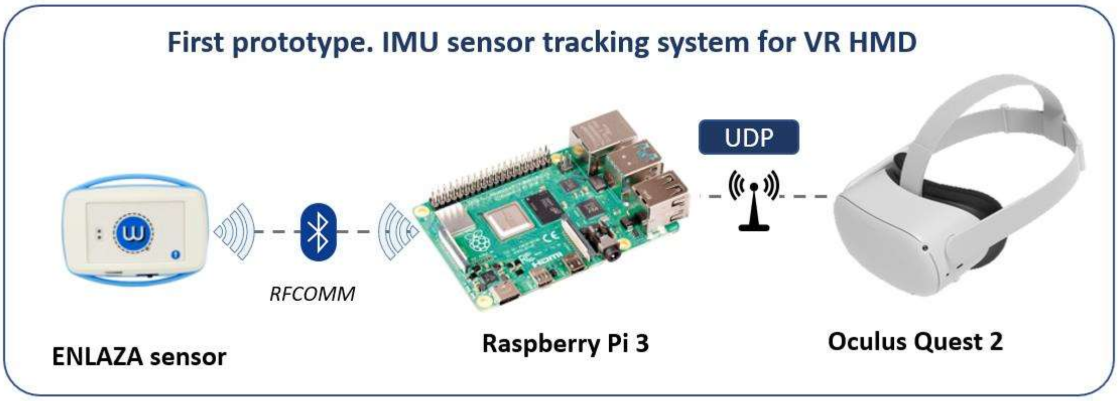

Figure 7. Schema of the first setup of the tracking system.

However, we sought to develop a system that would be independent of an intermediate CPU. The motion capture system was redesigned to reduce the required hardware elements to an inertial sensor and an HMD. This new approach entailed several modifications in the programming of the components to recognize the inertial sensor as a default peripheral by the Oculus Quest HMD. Subsequently, the motion analysis algorithm of the hip angle for pedalling cycle detection and cadence estimation was implemented (see Figure 8). By means of this algorithm, visual feedback of the movement can be provided to the user in the virtual environment in real time.

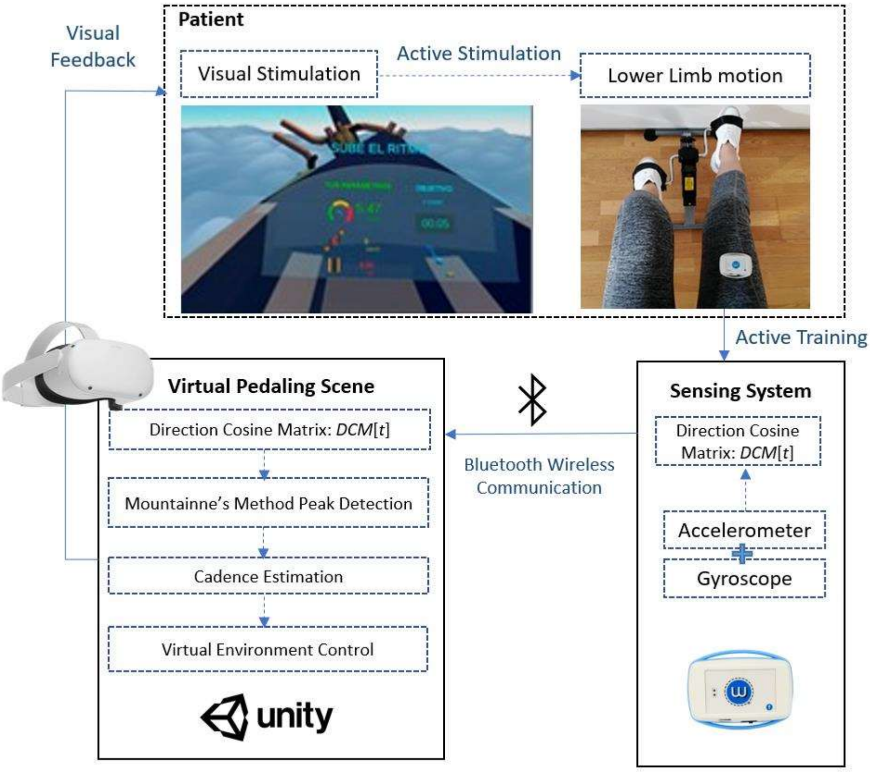

Figure 8. The overall workflow of the VR cycling platform, PedaleoVR.

Some aspects of the VR platform's design are summarized herein. The cycling VR platform was programmed with Unity3D software platform for Android 25 API Level for Oculus Quest 2 HMD. It is composed of 3 VE with different ambience scenery in which the user is in the steer cab of a vehicle which moves forward at the user's cycling speed. The speed information is mapped to those elements of the virtual environment that are moved to generate a perception of displacement. With these interrelations of effects, the user can observe how the conditions of his flight vary depending on his pedalling performance. This approach of using proprioceptive stimulation in VR as a strategy to involve the user in the physical activity is expected to promote engagement with the activity.

The feasibility validation of the tool in terms of accuracy and reliability was assessed in a pilot study with 13 health subjects. All participants performed 3 repetitions of 1-minute of pedalling at 3 different set-point speeds (30 rpm, 60 rpm, 90 rpm). The results of the statistical analysis highlighted the high concordance between the measurements taken by the MOTOmed™ system and Virtual Cycling Platform, called PedaleoVR, for slow (30rpm) and medium (60rpm) speed in both sessions. This indicates that its application would be suitable for low or moderate speed cycling exercise. Due to these good results in the technical validations, the next step consisted in the functional evaluation of the tool. It should be noted that this platform was designed to achieve greater adherence to cycling exercise using gamification strategies and user motivation for adults with LLD and older adults.

Finally, questions regarding to which extent this novel virtual cycling platform was perceived as a motivating and credible tool to increase cycling exercise in adults with LLD had not been addressed. Hence, our next goal was to validate several aspects of VR by two different populations, as two independent cases of study. To this end, two experimental trials were carried out with elderly people from Albertia Servicios Sociosanitarios and patients with lower limb disorders from Centro Lescer. After a single trial session, several standardized questionnaires were conducted, from which the following results were obtained. PedaleoVR was considered to be a credible and motivational tool towards adults with neuromotor disorders to perform cycling. In terms of usability, the participants with LLD rated PedaleoVR with an 80.37/100.00 in the SUS scale. From these positive assessments, it can be concluded that its use in patients with LLD could improve adherence to training due to the intrinsic characteristics of motivation and credibility. The safety of PedaleoVR was studied with elderly population, concluding that it does not generate negative effects related to cybersickness since the results obtained in all subscales of nausea, disorientation, and oculomotor scores were below 20 points in the pre-exposure and post-exposure evaluations. In addition, the sensation of presence and the degree of satisfaction generated by the virtual platform in the geriatric population have been positively evaluated. Also, regarding the acceptance and satisfaction of its use, the GUESS-18 subscales of personal gratification, play engrossment, narratives, and usability, were the highest rated subscales by elders. In general terms, it could be considered that PedaleoVR obtained a very positive acceptance in terms of satisfaction and usability.

The virtual reality cycling system can be used as daily activity in nursing homes or as home-based therapy. This very same idea of providing a home-based therapy solution has been pursued for designing the virtual reality application for upper limb. Among the purposes of this development is to offer a system that allows to continue ADL training at home. Despite that the scient literature in this field stated that patients with neuromotor pathologies are more motivated to perform PA training if they integrate ADL exercises, it is still vague on how to build feasible virtual reality tools for bimanual rehabilitation.

Consequently, **the main scientific contribution of this line of thesis work is to provide guidelines for the design of virtual reality environments for bimanual ADL exercises.** This proposed methodology consists of, first, identifying the movements of the daily life activity to be replicated in the VE. Secondly, to define the ranges of motion of each joint. And thirdly to generate a UX based on the achievement of goals, including the performance of the correct sequences of movements according to the predetermined ranges of motion. Therefore, to develop this application, considerable effort was invested in defining each of the movement sequences involved in each game. On the other hand, we opted for a bimanual game design given the scarcity of current systems that implement this strategy, despite that most of the actions that the person performs on a daily basis are bimanual. It is expected that bimanual strategy would promote the coordination of both sides, although movement fidelity in fine motor tasks would be limited.

This work gathers all the guidelines outlined to generate this VR tool. To verify that the design of the application is suitable for ADL training and the VR tool is usable, a study was carried out with 5 physiotherapists with expertise in neurorehabilitation and occupational therapy. All of them assessed whether each of the activities would be potentially useful to train the ADL exercise. Wisely, the 3 activities involving greater finger movement and object grasping were not considered optimal for this rehabilitation objective. While the 3 activities that did not require these finger fine movements were considered suitable for this purpose.

This study highlights the importance of fine movement detection in promoting functional upper limb rehabilitation. Moreover, having reviewed the state of the art in this field, it was found some VR applications that train finger movements employ haptic devices or robotic hardware. Although these solutions are preferable for training fine motor finger tasks, they can only work one side at a time. Thus, our approach complements these existing solutions by offering a VR tool designed for bimanual training.

Finally, this VR tool is part of two greater projects, POWERUP and JIRAFA research projects, that seeks to provide home-based therapy based on remote VR. To align the objectives of this tool with the technical requirements of remote VR computing, the use of OpenVR framework and HTC Vive Pro device was required. Then, in terms of technological innovation, a new approach for a remote virtual reality system for tele-rehabilitation is provided.

7.2. Conclusions

The main outcomes of this thesis are the design, development and validation studies of two virtual reality solutions for functional rehabilitation of people with motor disability. The first solution promotes PA of the lower limb based on pedalling in people with LLD. The second solution focuses on enabling functional ADL exercises for tele-rehabilitation of people with motor disabilities in the upper extremity. The ambition of this thesis is to study the technical design requirements for the construction of both systems. And generate gamified virtual environments whose purpose is to accurately assess the user's movement. To this end, algorithms for biomechanical and kinematic analysis of the movement in each activity (cycling, picking up objects, drinking water, washing hands, etc.) were implemented.

In line with the literature, the present thesis provides two novel solutions, and each has been evaluated according to its own objectives and with the appropriate target population. As a result of this extensive research, the following conclusions were reached:

PedaleoVR: Virtual reality cycling platform for lower limb training

Main finding 1: The accuracy of the ENLAZA™ sensor has proven to be superior to the Oculus Quest controller (Touch V2), and thus can be used as a motion tracker for virtual reality. In addition, the data sampling rate of the ENLAZA™ device is optimal to ensure an overall latency of 30Hz without breaking the user's sense of presence and body agency in VR.

Main finding 2: A technical validation of a low-cost wireless application in virtual reality (VR) for pedalling exercises based on a single inertial sensor and a commercial VR headset was achieved. In addition, this system is functional for any static cycling equipment and for any person, as the cycle estimation algorithm (based on the hip flexion-extension analysis) adapts to each individual's joint range.

Main finding 3: In terms of accuracy, it has been concluded that PedaleoVR detects cycles with high accuracy at low and moderate speeds and declines slightly at high speeds. Moreover, in terms of reliability or repeatability, the robustness and consistency of PedaleoVR measurements have been proven.

Main finding 4: The group of participants with LLD recognized PedaleoVR as a usable, motivating, and credible system for physical activity, although the ratings provided in the expectations subscale were low. This result reveals the patients' awareness that physical improvement will not come from using PedaleoVR but from exercising.

Main finding 5: The group of older participants recognized PedaleoVR as a usable and satisfying system from the point of view of interface quality and graphical aesthetics, as well as personal gratification and play engrossment. In addition, PedaleoVR was found to not cause adverse effects on the oculomotor, disorientation, and nausea domains.

FarmDay: Virtual Reality platform for ADL bimanual training

Main finding 6: The practice of daily life activities in virtual reality requires the design of gamified virtual environments that promote the precise performance of movements through goal-directed tasks strategies. To define these goals, it is essential to identify the movements to be worked on.

Main finding 7: To achieve complete functional rehabilitation, finger motion training should be allowed in conjunction with the rest of the upper limb segments. And for this, VR solutions that enable finger detection must be generated, either supported by CV hand-tracking or haptic wearables.

Main finding 8: At least 3 of the activities built under these design rules have been evaluated as suitable by experts. And overall, the FarmDay platform is proved to be a usable VR solution for home-based therapy.

7.3. Future work

FarmDay solution could be technically improved by exporting this development to other platforms that integrate hand-tracking for accurate finger and hand movement detection. It would also be desirable to integrate the ENLAZA™ inertial sensors to capture elbow and trunk movement. This would permit analysing movement compensations and avoids having to estimate motion from inverse kinematics. Once FarmDay is upgraded, a pilot study of the usability and effectiveness of the VR application with patients with SCI is to be conducted. We will characterize aspects of usability, design, virtual embodiment, and intrinsic motivation of the VR tool. Eventually, further studies to analyze adherence to the physical activity program and effectiveness of using the tele-rehab tool should be conducted with patients with upper limb motor disorders.

In relation to PedaleoVR, a study of the immediate impact of the system on

LLD patients has already been conducted during the period of this thesis and is pending publication. The conclusions of this study would contribute to add more information to the scientific evidence (Table 4). The significant difference in the improvement of TUG in the VRT group has been verified, but no statistically significant differences have been observed in the other metrics, and it could be said that they have improved equally in both groups.

The NeuroRehabilitation Group of the Cajal Institute has extensive experience in the use of electrical stimulation (ES) for functional rehabilitation. According to their earlier research, it has been confirmed that combination of functional electrical stimulation with pedalling activity could enhance bilateral symmetry. For this reason, we are already exploring the integration of electrical stimulation in PedaleoVR following the scheme shown in Figure 9. Nonetheless, it remains to explore its application in training sessions with patients with LLD to study its effects on bilateral symmetry and strengthening of the paretic side, along with the satisfaction of using the complete system.

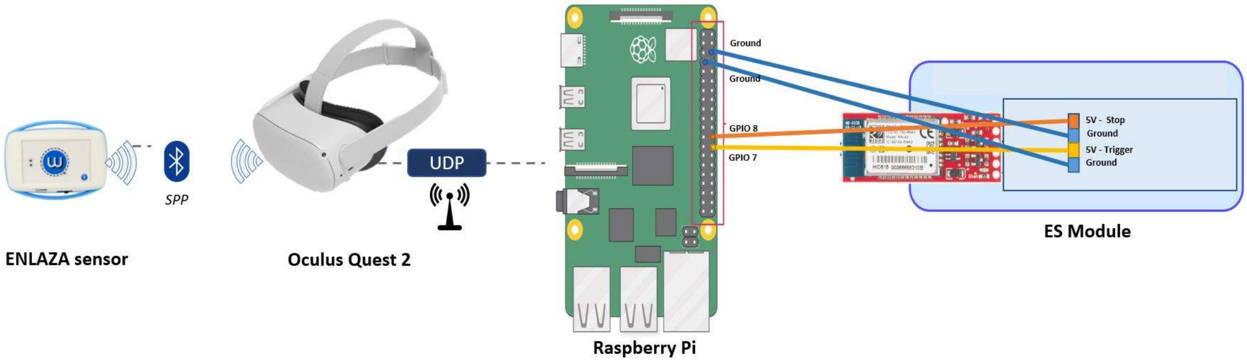

Figure 9. Schema of integration of electrical sttimulation in PedaleoVR.

A study combining PedaleoVR with auditory rhythmic stimulation is already underway. The hypothesis of this study is to contrast whether this combination of multisensory stimulation achieves a greater in performance, in terms of cadence. Since this line has been briefly explored by researchers at Aalborg University, Copenhagen (Brunn-Pedersen, Pedersen Kasper, Serafin, & Kofoed, 2014) (Høeg, y otros, 2021), (Gonzalez-Sanchez, Dahl, Hatfield, & Godøy, 2019), it is expected that an interesting collaboration could emerge between these parties to enhance this development.

SCIENTIFIC PUBLICATIONS

Journal Publications

1) **Rojo, A.**, Cortina, J., Sánchez, C., Urendes, E., García-Carmona, R., & Raya, R. (2022). Accuracy study of the Oculus Touch v2 versus inertial sensor for a single-axis rotation simulating the elbow's range of motion. *Virtual Reality*, 1-12.
    - Impact factor: 4.697, Q1 (Computer Science, Software Engineering; Computer Science, Interdisciplinary Applications)

2) **Rojo, A.**, Santos-Paz, J. A., Sánchez-Picot, Á., Raya, R., & García-Carmona, R. (2022). FarmDay: A Gamified Virtual Reality Neurorehabilitation Application for Upper Limb Based on Activities of Daily Living. *Applied Sciences*, 12(14), 7068.
    - Impact factor: 2.838, Q2 (Engineering, Multidisciplinary Sciences)

3) **Rojo, A.**, Raya, R., & Moreno, J. C. (2022) Virtual reality application for real-time pedalling cadence estimation based on hip ROM tracking with inertial sensors: a pilot study. *Virtual Reality*, 1-15
    - Impact factor: 4.697, Q1 (Computer Science, Software Engineering; Computer Science, Interdisciplinary Applications)

4) (Under review) **Rojo, A.**, Castrillo, A., López, C., Perea, L., Alnajjar, F., Moreno, J.C., Raya, R. (2022) PedaleoVR: Usability study of a virtual reality application for cycling exercise in patients with lower limb disorders and elders, *PLOS ONE*.
    - Impact factor: 3.752, Q1 (Multidisciplinary Sciences)

Book Chapters

1) Pozzi, M.; Radhakrishnan, U.; **Rojo, A.;** Koumaditis, K.; Chinello, F.; Moreno, J.C.; Malvezzi, M.; (2021) Exploiting VR and AR Technologies in Education and Training to Inclusive Robotics. In: Malvezzi, M., Alimisis, D., Moro, M. (eds) Education in & with Robotics to Foster 21st-Century Skills. EDUROBOTICS 2021. Studies in Computational Intelligence, vol 982. Springer, Cham. https://doi.org/10.1007/978-3-030-77022-8_11

International Conferences

1) **Rojo, A.;** Raya, R.; Moreno, J. C. (2020) Real-Time Cycling Cadence Estimation Using an Inertial Sensor for Gamified Pedaling Therapy In: Torricelli, D., Akay, M., Pons, J.L. (eds) Converging Clinical and Engineering Research on Neurorehabilitation IV. ICNR 2020. Biosystems & Biorobotics, vol 28. Springer, Cham. https://doi.org/10.1007/978-3-030-70316-5_107

2) **Rojo, A**.; Del Riego, S.; Sánchez, C.; Urendes, E. J.; García-Carmona, R.; Lerma-Lara, S.; Raya, R. (2022) POWERUP: A 3D-Printed Exoskeleton and Serious Games for the Rehabilitation of Children with Motor Disabilities. In: Miesenberger, K., Kouroupetroglou, G., Mavrou, K., Manduchi, R., Covarrubias Rodriguez, M., Penáz, P. (eds) Computers Helping People with Special Needs. ICCHP-AAATE 2022. Lecture Notes in Computer Science, vol 13342. Springer, Cham. https://doi.org/10.1007/978-3-031-08645-8_27