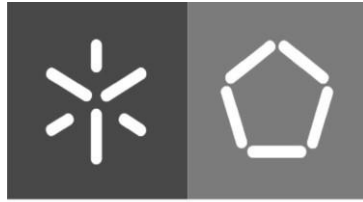


Universidade do Minho
Escola de Engenharia

Diana Raquel Barroso Gonçalves Rito

Virtual reality tool for balance training



Universidade do Minho
Escola de Engenharia

Diana Raquel Barroso Gonçalves Rito

Virtual reality tool for balance training

Dissertação de Mestrado

Mestrado Integrado em Engenharia Biomédica

Ramo Eletrónica Médica

Trabalho realizado sob a orientação de

Professora Doutora Cristina P. Santos

Doutora Joana Figueiredo

DIREITOS DE AUTOR E CONDIÇÕES DE UTILIZAÇÃO DO TRABALHO POR TERCEIROS

Este é um trabalho académico que pode ser utilizado por terceiros desde que respeitadas as regras e boas práticas internacionalmente aceites, no que concerne aos direitos de autor e direitos conexos.

Assim, o presente trabalho pode ser utilizado nos termos previstos na licença abaixo indicada.

Caso o utilizador necessite de permissão para poder fazer um uso do trabalho em condições não previstas no licenciamento indicado, deverá contactar o autor, através do RepositóriUM da Universidade do Minho.

Licença concedida aos utilizadores deste trabalho



Atribuição-NãoComercial-SemDerivações
CC BY-NC-ND

<https://creativecommons.org/licenses/by-nc-nd/4.0/>

AGRADECIMENTOS

E assim termina mais um capítulo da minha vida. O que fez passar de menina a mulher. Foram 5 anos intensos, com muito trabalho, empenho e dedicação depositados no curso que me vai permitir tornar Mestre em Engenharia Biomédica. O percurso nem sempre foi fácil, muitas noites mal dormidas, estudo e trabalhos até às tantas, mas sei que foi por um bom motivo e, olhando agora para trás, tudo valeu a pena. Foram 5 anos onde cresci e me desenvolvi não só em termos profissionais, mas também como pessoa. Onde me dediquei não só ao meu percurso académico, como também ao núcleo de estudantes do meu curso (GAEB), sempre com a esperança e certeza de que poderia dar um pouco de mim, para dar mais um pouco aos outros. No fundo, só queria tornar os 5 anos de alguém tão enriquecedores quanto os meus, repletos de experiências e vivências que vão ficar para sempre. Sim, porque não foram só noites mal dormidas, foram também anos onde me diverti muito e as memórias vão ficar para sempre comigo e para aqueles com quem as partilhei.

Restam-me, por isso, os agradecimentos. Não basta só lembrar, mas sim agradecer a quem me proporcionou tudo isto. Os meus maiores agradecimentos vão para a minha família, sobretudo aos meus pais, irmão e avós, que sempre me fizeram acreditar nas minhas capacidades e que festejaram comigo as minhas vitórias. Quero agradecer especialmente à minha mãe, por todo o esforço, empenho e dedicação que sempre teve e continua a ter, comigo e com o meu irmão, para que tenhamos tudo e só nos foquemos nos nossos estudos, com vista a um futuro promissor.

Seguidamente, quero agradecer aos meus colegas de curso. Destes, obviamente, com especial destaque para o Miguel, o meu companheiro de todas as horas, no bem e no mal. O meu melhor amigo e namorado. Em seguida, quero agradecer ao Rafael, o meu parceiro de mestrado e amigo, com quem partilhei muitas dores de cabeça em trabalhos sem fim à vista, mas também muitos bons momentos. Deixo ainda menção para o Miguel Castro, uma das melhores pessoas que a universidade me deu, em conjunto com as supramencionadas.

Por fim, mas não menos importante, quero agradecer à minha orientadora, professora Doutora Cristina P. Santos, pela orientação e oportunidade de trabalhar neste projeto. Quero também agradecer à Doutora Joana Figueiredo, coorientadora e colega, por toda a ajuda e apoio que sempre me disponibilizou. Por fim, quero agradecer à Cristiana, que foi comigo uma pessoa incansável, super dedicada e que sempre me acompanhou neste último ano.

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

RESUMO

Em todo o mundo, 15 milhões de pessoas sofrem um acidente vascular cerebral (AVC) por ano. Destas, 66% sobrevivem e metade delas ficam com incapacidade permanente de equilíbrio, limitando a sua independência motora e qualidade de vida. Estes pacientes podem recuperar o seu equilíbrio e independência motora através do fenómeno da neuroplasticidade, alcançado com intervenções de reabilitação. As ferramentas de realidade virtual (RV) podem ser utilizadas como complemento às terapias físicas convencionais, promovendo treinos de alta repetição com estratégias de aprendizagem otimizadas. Assim, os ambientes virtuais podem ser personalizados de acordo com as necessidades iminentes dos pacientes, maximizando a reorganização do cérebro e plasticidade, aumentando a eficácia e acelerando a recuperação do equilíbrio. Não obstante, existe uma falta de ferramentas de RV neste campo, as quais não apresentam uma visão centrada no utilizador.

Esta dissertação tem como objetivo conceber, desenvolver e validar uma ferramenta totalmente imersiva baseada em RV, seguindo uma visão centrada no utilizador. A ferramenta de RV desenvolvida inclui quatro desafios virtuais baseados em atividades do dia-a-dia (ADDs), compreendendo um total de nove tarefas motoras. A ferramenta de RV fornece estímulos visuais, sonoros e hápticos, através de óculos de RV, auscultadores incorporados, e comandos vibratórios. Paralelamente, foi realizado um estudo sobre as ADDs mais realizadas e apreciadas, com recurso a um questionário, provando que os desafios virtuais concebidos estão de acordo com a preferência da maioria das pessoas.

A partir de uma validação preliminar com sujeitos saudáveis, verificou-se que a ferramenta de RV melhorou significativamente o deslocamento do centro de massa (CDM) na direção mediolateral (ML) e a velocidade mínima do CDM na direção anteroposterior (AP), durante a marcha. Além disso, o deslocamento do CDM e a velocidade máxima e mínima do CDM, nas direções AP e ML, embora não significativas, exibiram melhorias noutras tarefas motoras. Os testes clínicos também revelaram uma melhoria após o treino RV. A avaliação da experiência do utilizador provou a elevada aceitabilidade, valor e utilidade da ferramenta de RV. O trabalho futuro envolve a melhoria da ferramenta com mais e personalizados desafios virtuais e a validação do sistema com doentes durante treinos mais longos.

PALAVRAS-CHAVE: ADDs, AVC, CDM, reabilitação de equilíbrio, realidade virtual

ABSTRACT

Worldwide, 15 million people suffer a stroke each year. Of these, 66 % survive and half of them are left with permanent balance disabilities, limiting their motor independence and compromising their quality of life. The patients can recover their balance function and regain their motor independence through neuroplasticity phenomenon, achieved by rehabilitation intervention. Virtual reality (VR) tools may be used as a complement to physical therapies to promote high-repetitive training with optimised learning strategies. Thus, virtual environments can be customised according to the patient's imminent needs, maximising brain reorganisation, allowing to increase the effectiveness and accelerate balance recovery. Nonetheless, there is a lack of VR tools in this field, and no user-centered design is available.

This dissertation aims to design, develop, and validate a fully immersive VR-based tool, following a user-centered design. The developed VR tool includes four virtual challenges based on activities of daily living (ADLs), comprising a total of nine motor tasks. The VR-based tool provides visual, sonorous, and haptic stimuli, through a Head-Mounted Display (HMD), built-in headphones, and vibrotactile controllers. In parallel, a study about the most performed and appreciated ADLs was carried out, using a questionnaire, proving that the developed virtual challenges are in accordance with most peoples' preferences.

From a preliminary validation with healthy subjects, the VR tool significantly improved the user's center of mass (COM) displacement in the mediolateral (ML) direction, and the minimum COM velocity in the anteroposterior (AP) direction when walking. Moreover, COM displacement and the maximum and minimum COM velocity on both AP and ML directions, although not significantly, also showed improvements in many other tasks. Furthermore, clinical tests revealed improvements after VR training. The user experience evaluation proved the high acceptability, value, and usefulness of the VR-based tool. Future work towards enhancing the VR-based tool with more and customised virtual challenges and extending the VR tool validation with end-users throughout a longer training period.

KEYWORDS: ADLs, balance rehabilitation, COM, stroke, virtual reality

CONTENTS

Agradecimientos.....	v
Resumo.....	vii
Abstract.....	viii
List of Figures.....	xii
List of Tables.....	xv
List of Acronyms.....	xxi
1. Introduction	1
1.1 Motivation and Problem Statement	1
1.2 Goals	3
1.3 Research Questions.....	4
1.4 Contribution to Knowledge.....	5
1.5 Dissertation Outline	5
2. Review on virtual reality tools for post-stroke balance rehabilitation.....	7
2.1 Methodology	7
2.2 Results.....	7
2.2.1 VR technology.....	10
2.2.2 Sensor integration.....	10
2.2.3 Motor tasks	11
2.2.4 Virtual challenges and control strategies.....	12
2.2.5 Clinical outcomes	16
2.3 Discussion	17
2.4 Conclusions	18
3. System description: VR-based tool for balance training.....	20
3.1 VR technology	20
3.2 Sensor integration	22
3.3 Motor tasks	25
3.4 Virtual challenges and VRE	25
3.5 Control strategies	30
3.5.1 First and second person views	31

3.5.2	Grab motion	32
3.5.3	Vibrotactile feedback.....	33
3.5.4	Visual and auditory feedback.....	33
3.5.5	Stepping up the ladder.....	34
3.5.6	Shelves height	34
3.6	Conclusions	35
4.	Questionnaire for User-centered design	36
4.1	Questionnaire about ADLs requiring balance	36
4.2	Participants.....	37
4.3	Descriptive Analysis.....	37
4.4	Results.....	37
4.4.1	Global results	38
4.4.2	Age	39
4.4.3	Gender	41
4.4.4	Degree of daily physical activity	43
4.4.5	Health condition	44
4.4.6	Degree of home urbanization	46
4.4.7	Type of transport daily used	47
4.4.8	Conventional physical therapy.....	49
4.5	Discussion	50
4.5.1	Conventional physical therapy.....	52
4.6	Conclusions	53
5.	Validation protocol	54
5.1	Participants.....	54
5.2	Intervention.....	55
5.3	Data Collection.....	57
5.4	Data processing	61
5.5	Statistical Analysis.....	61
5.6	Conclusions	62
6.	Results and discussion.....	63

6.1	During VR Intervention.....	63
6.1.1	Fruit Catcher	63
6.1.2	Take a Shower.....	66
6.1.3	Cooking.....	70
6.1.4	Watch Tv	72
6.2	Before vs after VR intervention	77
6.3	User's experience evaluation.....	89
6.4	Conclusions	91
7.	Conclusions.....	92
7.1	Future Work	95
	References	96
	Appendix I – Primary and secondary outcome measures	103
	Appendix II – Normality and homogeneity statistical tests	125
	Appendix III – User's experience evaluation	144

LIST OF FIGURES

Figure 3.1 - HTC Vive Pro Full Kit composed by a VR headset, two controllers, and two base stations [53].	20
Figure 3.2 - Xsens MVN Awinda: A) MVN Wireless Motion Tracker (MTw); B) MVN Awinda MTw's position on body with adjustable straps; C) MVN Awinda station [58]	23
Figure 3.3 - MVN Analyze Pro software: A) User's body dimensions to scale the Xsens biomechanical model; B) Datagram selected.	24
Figure 3.4 - House backyard design	27
Figure 3.5 - Apple tree with the ladder.....	27
Figure 3.6 - Kitchen division design	28
Figure 3.7 - Kitchen shelves.....	28
Figure 3.8 - Bathroom division design	29
Figure 3.9 - Bathtub used in the "Take a Sower" game.....	29
Figure 3.10 - Living room division design.....	30
Figure 3.11 - Mvn avatar facing the Z-axis in Unity environment [67].	31
Figure 3.12 – Watch Tv virtual challenge: A) In first person view; B) In first person view, with the second real-time view.	32
Figure 3.13 - HTC controllers' buttons and respective caption [68].....	33
Figure 4.1 - Number of subjects, in percentage, by activity, considering the five activities, out of fifteen, that people perform the most.....	38
Figure 4.2 - Number of subjects, in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most	38
Figure 4.3 - Number of the individuals by age (16-40 years, 40-66 years, > 66 years)	39
Figure 4.4 - Number of subjects by age (16-40, 40-66, > 66 years), in percentage, by activity, considering the five activities, out of fifteen, that people do the most	40
Figure 4.5 - Number of subjects by age (16-40, 40-66, > 66 years), in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most	40
Figure 4.6 - Number of subjects by gender (female and male), in percentage, by activity, considering the five activities, out of fifteen, that people do the most	42
Figure 4.7 - Number of subjects by gender (female and male), in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most	42

Figure 4.8 - Number of subjects by degree of daily physical activity (active and not active), in percentage, by activity, considering the five activities, out of fifteen, that people do the most.....	43
Figure 4.9 - Number of subjects by degree of daily physical activity (active and not active), in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.....	44
Figure 4.10 - Number of subjects with and without disease, in percentage, by activity, considering the five activities, out of fifteen, that people do the most.....	45
Figure 4.11 - Number of subjects with and without disease, in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.....	45
Figure 4.12 - Number of subjects living in the city and in countryside, in percentage, by activity, considering the five activities, out of fifteen, that people do the most.....	46
Figure 4.13 - Number of subjects living in the city and in countryside, in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.....	47
Figure 4.14 - Number of subjects who commute by motorised or non-motorised transport, in percentage, by activity, considering the five activities, out of fifteen, that people do the most.....	48
Figure 4.15 - Number of subjects who commute by motorised or non-motorised transport, in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.....	48
Figure 4.16 - Number of the individuals, in percentage, who do, did, or did not do physical therapy and whether they felt/feel or not motivated during sessions	49
Figure 4.17 - Number of people, in percentage, among those who do not felt/feel motivated, by reasons (tiring, boring, demanding, other) for such discontentment about conventional physical therapy.....	50
Figure 5.1 - Participant 6 during VR training. (A) While catching apples in “Fruit Catcher” virtual challenge. (B) While walking in “Watch TV” virtual challenges. (C) While collecting food from the kitchen shelves in “Cooking” virtual challenge. (D) While entering in the bathtub in “Take a Shower” virtual challenge.	56
Figure 6.1 - COM displacement (cm) in the AP direction by the ML direction, for all participants in each trial during the tasks of climbing stairs and catching fruits, of the virtual challenge "Fruit Catcher"	63
Figure 6.2 - COM displacement (cm) in the AP direction by the ML direction for all participants in each trial during the tasks of entering in the bathtub and standing on one leg inside the bathtub, of virtual challenge "Take a Shower"	67
Figure 6.3 - COM displacement (cm) in the AP direction by the ML direction for all participants in each trial while collecting food from the kitchen shelves in the virtual challenge "Cooking".....	70

Figure 6.4 - COM displacement (cm) in the AP direction by the ML direction for all participants in each trial while performing the three motor tasks of the virtual challenge “Watch Tv”: stand-to-sit, sit-to stand, and walking	73
Figure 0.1 - Scores of the Spatial Presence, Involvement, Experienced Realism, and Global Presence of the IPQ for the six participants	144
Figure 0.2 - Scores of the Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, and Value/Usefulness of the IMI questionnaire for the six participants.	144

LIST OF TABLES

Table 2.1 - Characteristics of the included studies	8
Table 3.1 - Specifications of HTC Vive Pro's headset and controllers [53]	21
Table 3.2 - Comparison of recommended system requirements to use Vive Pro [54] and the specifications of the used computer (ROG Strix Helios) [55][56]	22
Table 3.3 - Virtual challenges and respective motor tasks.....	26
Table 3.4 - Counter type furniture's height (cm) according to the user's height (cm)	35
Table 5.1 – Gender, age (years), height (m), and body mass (kg) of each participant.....	55
Table 5.2 – Virtual challenges and their respective outcome measures	59
Table 5.3 – Clinical scales and their respective outcome measures	60
Table 6.1 - Mean and SD of T1 and T2, and p-value of the paired samples test and Wilcoxon test for COM displacement (Disp) and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for climbing stairs and catching fruits motor tasks of the virtual challenge “Fruit Catcher”, considering the time condition and a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	64
Table 6.2 – Mean and SD of the ROM of the left and right knee joint angles on the sagittal plane (degrees), and the maximum hand position to the left, right, and forward directions (cm) in each trial of the virtual challenge “Fruit Catcher”	65
Table 6.3 – Number of steps climbed, and number of apples caught in each trial of climbing stairs and catching fruits, respectively, in virtual challenge “Fruit Catcher”	65
Table 6.4 - Mean and SD of T1 and T2, and the p-value of the paired samples test and Wilcoxon test for COM displacement (Disp) and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for entering in the bathtub and standing on one leg inside the bathtub inside the bathtub motor tasks of the virtual challenge “Take a Shower”, considering the time condition and a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	68
Table 6.5 - Mean and SD of the ROM of the left and right knee joint angles on the sagittal plane (degrees) in each trial of the virtual challenge “Take a Shower”	69
Table 6.6 - Number of times the user kicked the bathtub rim, and sound playing duration inside bathtub (s) in each trial of entering in the bathtub and standing on one leg inside the bathtub, respectively, in virtual challenge “Take a Shower”	69

Table 6.7 - Mean and SD of T1 and T2, and the p-value of the paired samples test and Wilcoxon test for COM displacement (Disp) and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for collect the food of the kitchen shelves, of the virtual challenge “Cooking”, considering the time condition and a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	71
Table 6.8 - Number of ingredients caught in kitchen’s shelves in each trial of the virtual challenge “Cooking”	71
Table 6.9 - Mean and SD of T1 and T2,, and the p-value of the paired samples test and Wilcoxon test for COM displacement (Disp) and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for stand-to-sit, sit-to-stand, and walking motor tasks of the virtual challenge “Watch Tv”, considering the time condition and a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	74
Table 6.10 – Mean and SD of the ROM of the left and right knee joint angles on the sagittal plane (degrees) for stand-to-sit, sit-to-stand, and walking motor tasks, and the stride length (cm) and stride time (s) for walking motor task in each trial of the virtual challenge “Watch Tv”	75
Table 6.11 – Television state achieved in each trial of the virtual challenge “Watch Tv”	76
Table 6.12 - Mean and SD of pre and post VR training trials, and the p-value of the paired samples test and Wilcoxon test for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for BBS’ tasks, considering the time condition and a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	78
Table 6.13 - Mean and SD of T1 and T2, and the p-value of the paired samples test and Wilcoxon test for COM displacement (Disp) and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for sit-to-stand, walking, and stand-to-sit motor tasks of TUG, considering the time condition and a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	83
Table 6.14 - Mean and SD of the ROM of the left and right knee joint angles on the sagittal plane (degrees) for sit-to-stand, stand-to-sit, place alternate foot on step, and standing on one leg, and the maximum hand position (cm) for reaching forward BBS’s tasks.....	84
Table 6.15 - Mean and SD of the ROM of the left and right knee joint angles on the sagittal plane (degrees) for sit-to-stand, walking and stand-to-sit motor tasks, and the stride length (cm) and stride time (s) for walking motor task in each trial of TUG clinical scale	85
Table 6.16 – Final scores for BBS and TUG clinical tests, for each of the participants, before and after the VR intervention	85

Table 6.17 - Mean and SD for pre and post VR training, the p-value of the paired samples test, and the p-value of the Wilcoxon test for BBS and TUG clinical tests, considering the time condition and a significance level of 5 %	86
Table 6.18 - Mean and standard deviation (SD) of all the participants, for each factor of IPQ.....	89
Table 6.19 - Mean and standard deviation (SD) of all the participants, for each subscale of IMI	90
Table 6.20 - Participants' answers to the open questions of the Value/Usefulness subscale of IMI questionnaire	90
Table 0.1 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), and number of steps climbed by each participant, in both trials, while climbing stairs (CS), in Fruit Catcher virtual challenge	104
Table 0.2 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), maximum hand position (m) for left, forward and right directions, and number of apples caught by each participant, in both trials, while catching fruits (CF), in Fruit Catcher virtual challenge	105
Table 0.3 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), and number of times each participant kicked the bathtub rim, in both trials, while entering to the bathtub (EB), in Take a Shower virtual challenge.....	106
Table 0.4 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), and the amount of time the sound played (s) 10 s being the total, in both trials, while each participant is inside the bathtub (IB), in Take a Shower virtual challenge.....	107
Table 0.5 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and the number of ingredients caught, in both trials, by each participant, in Cooking virtual challenge.....	108
Table 0.6 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and ROM of both left and right knee joint angle on the sagittal plane (degrees) of each participant while sitting, in both trials, in Watch Tv virtual challenge	109
Table 0.7 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and ROM of both left and right knee joint angle on the sagittal plane (degrees) of each participant while standing, in both trials, in Watch Tv virtual challenge	110

Table 0.8 – Mean and standard deviation of COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), stride time (s), and stride length (m) of each participant while walking, in both trials, and if he turn on the television, in Watch Tv virtual challenge	111
Table 0.9 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), and the BBS score of each participant, for BBS tasks 1,4,12, and 14, respectively, before and after VR training.....	113
Table 0.10 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), maximum hand forward position (cm), and the BBS score of each participant, for BBS task 8, before and after VR training.....	115
Table 0.11 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and the BBS score of each participant, for the fourteen BBS tasks 2, 3, 5, 6, 7, 9, 10, 11, 13, respectively, before and after VR training	116
Table 0.12 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and ROM of both left and right knee joint angle on the sagittal plane (degrees) of each participant while performing the standing TUG task, in both trials, before and after VR training.....	121
Table 0.13 - Mean and standard deviation of COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), stride time (s), and stride length (m) of each participant while performing the TUG walking task, before and after VR training.....	122
Table 0.14 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and ROM of both left and right knee joint angle on the sagittal plane (degrees) of each participant while performing the TUG sitting task, before and after VR training	124
Table 0.15 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for CS, and CF motor tasks of the virtual challenge “Fruit Catcher”, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold.....	125
Table 0.16 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for EB, and standing on one leg inside the	

bathtub (IB) motor tasks of the virtual challenge “Take a Shower”, considering a significance level of 5 %.	
The most representative results (p-value < 0.05) appear in bold	126
Table 0.17 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, collecting food from the kitchen shelves of the virtual challenge “Cooking”, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	127
Table 0.18 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for stand-to-sit, sit-to-stand, and walking motor tasks of the virtual challenge “Watch Tv”, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold.....	128
Table 0.19 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for BBS motor tasks, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	129
Table 0.20 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for sit-to-stand, stand-to-sit, and walking motor tasks of TUG, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	134
Table 0.21 - The p-values of the normality tests for BBS and TUG scores, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	135
Table 0.22 - The p-values of the homogeneity test for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for CS, and CF motor tasks of the virtual challenge “Fruit Catcher”, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold.....	135
Table 0.23 - The p-values of the homogeneity tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for EB, and standing on one leg inside the bathtub (IB) motor tasks of the virtual challenge “Take a Shower”, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	136
Table 0.24 - The p-values of the homogeneity tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, collecting food from the kitchen shelves of the virtual challenge “Cooking”, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	137

Table 0.25 - The p-values of the homogeneity tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for stand-to-sit, sit-to-stand, and walking motor tasks of the virtual challenge “Watch Tv”, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	138
Table 0.26 - The p-values of the homogeneity tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for BBS motor tasks, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold.....	139
Table 0.27 - The p-values of the homogeneity tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for sit-to-stand, stand-to-sit, and walking motor tasks of TUG, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	143
Table 0.28 - The p-value of the homogeneity test for TUG scores, considering a significance level of 5 %. The most representative results (p-value < 0.05) appear in bold	143

LIST OF ACRONYMS

10 mWT – 10-meter Walking Test
3D – Three Dimensional
6 mWT – 6-minute Walking Test
ABC – Activities-specific Balance Confidence scale (ABC)
ADLs – Activities of Daily Living
AP – Anteroposterior
BBA – Brunel Balance Assessment
BBS – Berg Balance Scale
BI – Barthel Index
BiRD Lab – Biomedical Robotic Devices Laboratory
BPM – Balance Performance Monitor
BOS – Base of Support
CB&M – Community Balance and Mobility Scale
CMEMS – Centre of MicroElectroMechanical Systems
CMOS – Complementary Metal-Oxide Semiconductor
COM – Center of Mass
COP – Center of Pressure
CTSIB – Clinical Test for Sensory Interaction in Balance
DGI – Dynamic Gait Index
EMG - Electromyography
FAC – Functional Ambulatory Category
FAI – Frenchay Activity Index
FIM – Functional Independence Measure
FMA-LE – Fugl-Meyer Assessment oriented to Lower Extremity
FRT – Functional Reach Test
FSST – Four Step Square Test
FTSST – Five Times Sit-to-Stand Test
HMD – Head Mounted Display
IMI – Intrinsic Motivation Inventory
IPQ – Igroup Presence Questionnaire
IR - Infrared

K-MBI – Korean version of Modified Barthel Index
LRT-L/R – Lateral Reach Test Left/Right
MBI – Modified Barthel Index
ML – Mediolateral
MMAS – Modified Motor Assessment Scale
MMT – Manual Muscle Test
MoCA – Montreal Cognitive Assessment
POMA – Tinetti Performance-Oriented Mobility Assessment
PPT – Physical Performance Test
RGB - Red-Blue-Green
RNLI – Reintegration to Normal Living Index (RNLI)
ROM – Range of Motion
RT – Romberg’s Test
SIS – Stroke Impact Scale
sRT – sharpened Romberg’s Test
STOLL – Standing on The Left Leg
STORL – Standing on The Right Leg
TUG – Timed Up and Go Test
VR – Virtual Reality
VRE – Virtual Reality Environment
WAQ – Walking Ability Questionnaire

1. INTRODUCTION

This dissertation presents the work developed in the scope of the fifth year of the Integrated Master's in Biomedical Engineering, at the University of Minho, during the academic year of 2020-2021.

The academic year was passed working in the Biomedical Robotic Devices Laboratory (BiRD Lab), included in the Centre of MicroElectroMechanical Systems (CMEMS) Research Centre, at the University of Minho, Guimarães, Portugal. During this period, it was developed and validated a fully immersive virtual reality (VR) tool for balance training. This system was developed to improve the static and dynamic balance aiming at the rehabilitation process's acceleration. All the methods, results, and conclusions are detailed in this document.

1.1 Motivation and Problem Statement

Stroke affects annually 15 million people worldwide, predominantly over 40 years old and in 8% of children with sick cell disease [1]. Of these 15 million, 5 million survive but are left permanently disabled [1]. Due to this, stroke is the leading cause of serious long-term disability, usually including loss of balance, postural instability, muscle paralysis or muscles weakness, and impaired walking ability [2]. This and other neurological conditions (i.e., Parkinson's disease, cerebral palsy), ear disorders (i.e., ear infections, vestibular problems as inner ear abnormalities or Meniere's disease), head injury, and age (≥ 60 years old), as well as certain medications are the main leading causes of loss of balance [3], [4].

Balance is the ability to remain in a position (e.g., standing or sitting) or to move without losing postural control or falling [5]. Good balance requires the coordination of several parts of the body, such as muscles, bones, joints, central nervous system, and inner ear [6], which are usually affected by the problems mentioned above. Balance disorders are one of the main risk factors for falling, being the second leading cause of unintentional injury deaths worldwide [7], mostly in people over 65 years old [8]. The loss of balance itself and the associated fear of falling lead to people's loss of independence and increased difficulty to perform their activities of daily living (ADLs), compromising the quality of life, and professional and social inclusion [9]. According to the current situation, there is a need to focus on the improvement of balance recovery strategies.

People who survived and were left with disabilities can recover their balance function and regain their motor independence through neuroplasticity phenomenon. Neuroplasticity is the ability of the brain to redevelop its neural network and rewire functions at the healthy part of the brain by forming new

connections and pathways [10] to take over the role of the damaged part [11]. However, for this phenomenon to occur, it is necessary to stimulate the cells of the brain through exposure to frequent and repetitive activities [11], [12]. This can be achieved by rehabilitation intervention, either physical or robotic [11], [13]. Physical therapy, as conventional balance therapy, involves changing positions, breathing exercises, and exercise therapy in passive and active mobilization, with the guidance of a therapist [11]. Conventional rehabilitation has the disadvantages of being non-standard and dependent on the therapist's preference [11], [13].

Robotic therapy includes robotic devices with advanced control techniques, which allow interaction with the user, provide body-weight support, intense high-repetition training over a longer period, and optimised learning strategies, in opposition to conventional therapies [14]. Furthermore, some robotic devices are equipped with embedded sensors providing objective information about the user's motor condition and evolution of the user's performance, and also giving feedback to the user [14]. Feedback about the user's performance during training not only increase her/his motivation, but also facilitate the neuroplasticity phenomenon [15], and may improve the therapy's efficacy [16]. Moreover, robotic therapy is less therapist-dependent once a single physiotherapist can properly supervise multiple patients who train on different robotic devices [14]. However, the physiotherapists perform an essential and irreplaceable work once training with clinicians supervising show more clinically significant improvements than those without supervision [16]. There is evidence that combining both robotic and physical therapies improves and accelerates the user's recovery, once robot-assisted rehabilitation provides a standardized environment for all the patients, where therapy intensity and level of difficulty are adjusted according to the user's imminent needs [14], [15].

Current scientific works demonstrate that virtual reality (VR) can be a promising and powerful tool, as a robotic rehabilitation tool, in order to find an optimal solution for the rehabilitation of cognitive and motor functions [17]–[19]. VR offers the possibility to create endless three-dimensional (3D) virtual reality environments (VREs), as close as desired to the real ones, eliciting realistic perceptions and reactions in the user [17], [19]. Moreover, it is possible to design high-detailed environments that can be too dangerous, expensive, or impossible to create in physical reality by under full control and safety conditions to patient and the therapist [17]. Furthermore, VREs can be designed and customised by designing virtual challenges according to the user's imminent needs, which is critical for maximising brain reorganization and neuroplasticity phenomenon [20].

The user can experience more or less immersion in the VRE when using a Head-Mounted Display (HMD) or single screen, respectively [17]. Fully immersive scenarios bring the user inside the VRE, allowing her/him to feel that she/he is physically present in the observed environment [17]. This characteristic, also called “Sense of Presence”, can be useful once it allows obtaining realist physiological reactions from the user to virtual stimuli, as if the subject was really in a place identical to the virtual one [17]. On the other hand, fully immersive scenarios allow a more natural interaction with the surrounding environment [17]. Additional biosensors such as Inertial Measurements Units (IMUs), force sensors, and electromyography (EMG) sensors, by tracking the full-body patients’ kinematics, movement dynamics, and muscle activation [20], respectively, allows the user to interact with the virtual environment using her/his entire body as an active part of the 3D virtual world [17].

VR intervention has already been demonstrated to be effective in improving balance, physical disabilities, functional ability, and muscle strength in a large number of studies [21]. Moreover, some significant improvements were also obtained in clinical outcomes, such as Berg Balance Scale and Timed Up and Go Test, after VR intervention on post-stroke patients [21]. Furthermore, the satisfaction, adherence, engagement, enjoyment, and low pain of VR therapies can be highlighted, contrarily to the physical therapies [21]. However, these systems are designed for entertainment purposes, being this its first and main objective. Thus, there is a lack of immersive VR systems in the balance rehabilitation field, and there is yet no VR tool with a user-centered design that enables balance training oriented to patients’ needs in ADLs. Further, most of studies used non-wearable VR technology and biosensors, involved to provide real-time feedback of patients’ movements, limiting the VR tools to clinical practice to an indoor fixed facility. In this manner, there is a need to focus on the development of a wearable VR-based tool with a user-centered design for balance rehabilitation, aiming the acceleration of the recovery process.

1.2 Goals

The ultimate goal of this dissertation is to design, develop, and validate a fully immersive and wearable VR-based tool to be used as a promising complementary tool of physical balance therapy, aiming at the acceleration of the balance rehabilitation process. Fully immersive VREs will be developed to be the most realistic and identical as possible to the real world to obtain realist physiological reactions from the user to virtual stimulus. The user will be immersed through VR glasses in VREs controlled in real-time by inertial data from wearable sensors, providing feedback and, consequently, encouraging the users to execute static and/or dynamic balance tasks to complete the virtual challenges induced by an enthusiast serious game. User-centered strategies will be used to design the VREs according to the users’ imminent

needs in their daily routine. Thus, the proposed VREs match the most performed ADLs to train the balance of post-stroke survivors such they are able to independently perform their ADLs. Further, these user-centred strategies will be developed to maximize the users' acceptability, enthusiasm, and willingness during VR-based balance training.

To reach this main goal, it is necessary to achieve the following step-objectives:

- **Objective 1:** Literature review of the most recent developed VR-based tools for post-stroke balance rehabilitation. This review aims to find the specifications of VR-based tools, such as VR technology, embedded sensors, motor tasks, virtual challenges, control strategies, and clinical outcomes, advancing current literature reviews. The results from the selected studies should be analysed to guide and accelerate future research on user-centered design of VR-based post-stroke balance rehabilitation. This is addressed in Chapter 2.
- **Objective 2:** Identify the static and dynamic balance tasks and related virtual challenges that must be performed by the users towards a balance training driven by ADLs, following a user-centered design and the specifications reviewed in Chapter 2. This is addressed in Chapter 3.
- **Objective 3:** Design, develop, and control the VREs considering the defined virtual challenges. The control should be performed in real-time using wearable commercial-available inertial and fully immersive VR systems. This is addressed in Chapter 3.
- **Objective 4:** Develop a brief questionnaire to assess the most performed and appreciates ADLs by people to verify if the developed VREs match the user's needs. This is addressed in Chapter 4.
- **Objective 5:** Validate the VR-based tool effects in balance training involving healthy subjects. The validation protocol should be designed and implemented to preliminarily evaluate the tool's operability and effectiveness. The tool's acceptability and user's experience should be assessed through questionnaires. This is addressed in Chapters 5 and 6.

1.3 Research Questions

In order to achieve the main goal, the following Research Questions (RQs) were identified and answered:

- **RQ1:** What specifications should be considered for the user-centered design of VR-based post-stroke balance rehabilitation? The answer is included in Chapter 2.

- **RQ2:** What factors should be considered for a user-centered design of a VR-based tool in balance training? The answer is included in Chapter 4.
- **RQ3:** Which are the effects of a fully immersive VR-based tool in balance training? The answer is included in Chapter 6.

1.4 Contribution to Knowledge

The main contributions of this dissertation to knowledge are:

- A review of the most recent developed VR-based tools to improve the balance recovery of stroke survivors;
- A novel fully-immersive VR-based tool for balance training following a user-centered design;
- A questionnaire about the most performed and appreciated ADLs requiring balance;
- Evidence regarding the influence of age, gender, degree of daily physical activity, health condition, degree of home urbanization, and type of transport daily used on the most performed and appreciated ADLs;
- Evidence concerning the kinematic effects and acceptability of a VR-based tool in balance training.

The work developed during this dissertation allowed the publication of the following conference paper:

- **D. Rito, C. Pinheiro, J. Figueiredo, C. P. Santos,** "Virtual Reality tools for post-stroke balance rehabilitation: a review and a solution proposal", IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC), Santa Maria da Feira, Portugal, 2021.

1.5 Dissertation Outline

This dissertation is organized into 7 chapters, as follows.

Chapter 2 presents the state-of-the art of the VR-based tools for post-stroke balance rehabilitation. The specifications of VR-based tools are presented and discussed, regarding the VR technology, embedded sensors, motor tasks, virtual challenges, control strategies, and clinical outcomes.

Chapter 3 addresses the description of the VR-based tool. Firstly, the hardware included in the developed VR-based tool is announced, mentioning its need and technical characteristics. Secondly, the

user-centered design of the VR-based tool is presented, identifying the motor tasks and virtual challenges. Thirdly, the developed VREs and control strategies to allow user-VRE interaction are described.

Chapter 4 presents the developed questionnaire to assess the most performed and appreciated ADLs. Also in this chapter, the results are presented by the factor (age, gender, degree of daily physical activity, health condition, degree of home urbanization, and type of transport daily used) in order to understand if any of these factors influence the people's preferences.

Chapter 5 describes the validation protocol executed by healthy participants to assess VR-based tool's operability and effectiveness, and user's experience in balance training.

Chapter 6 presents and critically discusses the results of the VR-based tool's operability and effectiveness, and user's experience from Chapter 5.

Chapter 7 addresses the conclusions of this dissertation, answering the research questions and appointing future work.

2. REVIEW ON VIRTUAL REALITY TOOLS FOR POST-STROKE BALANCE REHABILITATION

A review of VR-based tools for post-stroke balance rehabilitation is essential to accelerate future investigations, considering the advantages that these technologies can bring to post-stroke rehabilitation. Current reviews on this topic, like the ones from Mohammadi et al. [22] and D. Corbetta et al. [23], focus on the clinical effects of VR on post-stroke balance. However, they lack describing the specifications beyond these tools such as VR technology, embedded sensors, motor tasks, virtual challenges, control strategies, and clinical outcomes. Thus, this chapter reviews these specifications of VR on post-stroke balance, advancing current literature reviews [22], [23], and aims to answer the following research question: What specifications should be considered for the design of VR-based post-stroke balance rehabilitation?

2.1 Methodology

The studies included in this review were searched in the Scopus, IEEE, and PubMed databases using the following keywords: “stroke”, “virtual reality”, “balance”, “rehabilitation”, and “training”. In the Scopus and IEEE databases, the search type was “Article title, Abstract, Keywords” and “All Metadata”, respectively, with the following combination: “stroke AND virtual reality AND balance AND rehabilitation”. In the PubMed database, the search type was “Title/Abstract” with the following combination: “stroke AND virtual reality AND (balance OR training)”. Only studies published after 2004 were considered.

The reference list of all the relevant found studies was checked. Among the resulting studies, only those comprising all the eligibility criteria were included in this review. The inclusion criteria were: (1) use VR equipment; (2) post-stroke patients; (3) aimed to improve balance control; (4) compare VR and conventional rehabilitation. The exclusion criteria were: (1) do not use VR equipment; (2) do not include post-stroke patients; (3) aimed to not improve balance control; (4) do not compare VR and conventional rehabilitation. The following specifications of VR-based tools were extracted: VR technology, sensor integration, motor tasks, virtual challenges, control strategies, and clinical outcomes.

2.2 Results

After deleting duplicate results and studies that did not meet inclusion criteria, 28 studies were analysed. The extracted characteristics of the included studies are shown in Table 2.1.

Table 2.1 - Characteristics of the included studies

Study	VR technology	Sensor integration	Motor tasks	Virtual challenges	Measured Outcomes
Barcala et al. (2013) [24]	TV Screen	Balance board	Not mentioned	Nintendo Wii Fit games: Plataformas, Pesca Bajo Cero, and Cuerda Floja	Berg Balance Scale (BBS), Timed Up and Go Test (TUG), and Functional Independence Measure (FIM)
Cho et al. (2012) [25]	TV Screen	Balance board	Not mentioned	Nintendo Wii Fit games: Balance Bubble, Ski Slalom, Ski Jump, Soccer Heading, Table Tiling, and Penguin Slide	BBS and TUG
Cho et al. (2013) [26]	Screen and loudspeakers	Not mentioned	Treadmill walking	Walking in a virtual scenario from a real-world video recording	BBS and TUG
Cho et al. (2014) [27]	Screen and a loudspeaker	Not mentioned	Treadmill walking	Walking in a virtual scenario from a real-world video recording	BBS and TUG
Huh et al. (2015) [28]	Screen	Balance board and tilting sensor	Horizontal weight shifting and knee flexion	Fruit-Harvesting game	BBS, Functional Ambulation Category (FAC), 6-minute Walking Test (6 mWT), TUG, Korean version of Modified Barthel Index (K-MBI), and Manual Muscle Test (MMT)
In et al. (2016) [29]	LCD Monitor	Camera	Dorsiflexion and plantarflexion; Adduction and abduction of forefoot and rear foot; Adduction and abduction of the hip	Mimic motor tasks	BBS, Functional Reach Test (FRT), TUG, 10-meter Walking Test (10 mWT)
Kim et al. (2009) [30]	TV Screen	Video-camera and cyber gloves	Weight shifting, stepping, trunk, pelvis, hip, knee, and ankle movement	IREX VR games: Stepping up/down, Sharkbait, and Snowboard	Balance Performance Monitor (BPM), BBS, 10 mWT, and Modified Motor Assessment Scale (MMAS)
Lee et al. (2012) [31]	Screen	Two electronic scales, an infrared camera, and four infrared markers	Weight shifting in both horizontal and vertical directions, knee flexion, and extension	Board Cleaner game	FAC, 10 mWT, TUG, BBS, K-MBI, and MMT
Lee et al. (2015) [32]	Monitor	Platform included in BioRescue system	Left-right and up-down weight shifting	City Walking, Hot air Balloon, and Bubble games	BBS and TUG
Lloréns et al. (2015) [33]	Video display and speakers	Two Opti Track FLEX:C120 cameras and two markers	Stepping	Reach virtual items that rose from the ground moving one foot while maintaining the other foot within a virtual circle	BBS, Tinetti Performance-Oriented Mobility Assessment (POMA), Brunel Balance Assessment (BBA), and 10 mWT
Park et al. (2013) [34]	HMD	Sensor that measures the patient's posture and movement.	Trunk stability and pelvic tilting in supine position; Trunk upright control and pelvic tilting in sitting position; Lower extremity muscle strengthening exercise; Weight-bearing; Upper extremity active movement	Mimic motor tasks	10 mWT
Park et al. (2017) [35]	Monitor	Kinect sensor (Red-Green-Blue [RGB] and infrared camera)	Active movement of the upper extremity, weight-shifting, weight-bearing, trunk rotation, active movement of the lower extremity (hip flexion, abduction, and external-internal rotation, knee flexion and extension, ankle dorsiflexion, and plantarflexion)	Xbox Kinect games: Boxing, Table Tennis, Soccer, Golf, Ski, and Football	Lower Extremity Fugl-Meyer Assessment (FMA-LE), BBS, TUG, and 10 mWT
Rajaratnam et al. (2013) [36]	TV Screen	Balance board and Kinect sensor	Nintendo Wii Fit: weight shifting during standing; Microsoft Kinect: COM change in both sitting and standing positions	Nintendo Wii Fit games	FRT, TUG, Modified Barthel Index (MBI), and BBS
Song et al. (2014) [37]	TV Screen	IREX: camera and red gloves; Tetrax: four force plates	IREX VR: center of pressure (COP) movement; Tetrax: not mentioned	IREX VR: five games; Tetrax: not mentioned	BBS

Study	VR technology	Sensor integration	Motor tasks	Virtual challenges	Measured Outcomes
Yatar et al. (2015) [38]	TV Screen	Balance board	Not mentioned	Nintendo Wii Fit games: Soccer Heading, Ski Slalom, and Balance Bubble	BBS, TUG, Dynamic Gait Index (DGI), FRT, Activities-specific Balance Confidence scale (ABC), and Frenchay Activity Index (FAI)
Jaffe et al. (2004) [39]	HMD with built-in headphones and pager vibrator	Video camera and flat foot switches	Walking and stepping	Step over virtual obstacles	POMA, Physical Performance Test (PPT), 6 mWT
Jung et al. (2012) [40]	HMD with built-in headphones	Not mentioned	Treadmill walking	Walking in a virtual park stroll	TUG and ABC
Kang et al. (2012) [41]	HMD with built-in headphones	Not mentioned	Treadmill walking	Walking in a virtual street	TUG, FRT, 10 mWT, and 6 mWT
Mirelman et al. (2009) [42]	Computer Monitor	Stewart platform included in the Rutgers Ankle Rehabilitation System	Dorsiflexion, plantar flexion, inversion, and eversion	Navigate a virtual plane or boat towards a series of targets	7-meter walkway, 6 mWT, FMA-LE, and BBS
Morone et al. (2014) [43]	TV Screen	Balance board	Not mentioned	Nintendo Wii Fit games: Hula Hoop, Bubble Blower, and Sky Slalom	BBS, Barthel Index (BI), FAC, and 10 mWT
Yang et al. (2008) [44]	three connected screens and three-dimensional auditory outputs	Electromagnetic system	Treadmill walking	Walking in a virtual community	ABC, Walking Ability Questionnaire (WAQ)
Quratul et al. (2021) [45]	LCD	Kinect sensor	Dodge left and right, duck, jump	Xbox Kinect games: 20 000 Leaks, River Rush, and Reflex Ridge	BBS and TUG
Xu et al. (2021) [46]	Monitor	PrimeSense 3D Awareness Sensor	Hip and knee flexion and extension, and single-legsupport	Stomp Joy game	FMA-LE, MBI, and BBS
Cikajlo et al. (2020) [47]	LCD screen	Balance board and Kinect sensor (RGB camera)	Weight shifting, standing on a single leg, stepping, squats	Animal Hurdler, Fruit Catcher, and Horse Runner games	Four Step Square Test (FSST), TUG, 10 mWT, Romberg's Test (RT), sharpened Romberg's Test (sRT), Standing On the Left Leg (STOLL), Standing On the Right Leg (STORL), and Clinical Test for Sensory Interaction in Balance (CTSIB)
Fishbein et al. (2019) [48]	TV screen	Web video camera	Treadmill walking	Ball Game, Reactive Boxing, and Cleaning Windows games	10 mWT, TUG, FRT, Lateral Reach Test Left/Right (LRT-L/R), ABC, and BBS
Mazzini et al. (2019) [49]	Three projectors and a sound system	Force platform and six infrared cameras	Weight shifting, stepping, knee flexion and extension, hands' movements	Balloon Pop, City Ride, Hit the Mole, 2d Maze, Road Encounters, Road Stepping, Paper Flight, and Hit Knees games	Stroke Impact Scale (SIS), Montreal Cognitive Assessment (MoCA), BBS, 6 MWT, 10 mWT, and TUG
Sheehy et al. (2019) [50]	TV screen	Kinect sensor	Standing, reaching, stepping, standing hip abduction, arm circles, sit-to-stand, aerobic exercises	Slalom Skiing and Whack-a-Mole games, and several activities	BBS, TUG, Five Times Sit-to-Stand Test (FTSST), Community Balance and Mobility Scale (CB&M), SIS, and Reintegration to Normal Living Index (RNLI)
Zanona et al. (2018) [51]	Projector	Kinect sensor	Weight shifting	Nintendo Wii Fit games: Boxing, Bowling, Snowboarding, Swimming, and Tennis	BBS and FIM

2.2.1 VR technology

The VR technology used in the reviewed studies provides visual (28 studies) and/or auditory (21 studies) cues to patients. The study [39] is the only which provides vibrotactile cues through a pager vibrator.

By analysing Table 2.1, it is possible to visualize three types of display systems (i.e., screen, a combination of screens, HMD) commonly used to provide visual feedback to patients in VR-based balance rehabilitation. Twenty two studies provided access to the virtual environment through a television (TV) screen [24], [25], [30], [36]–[38], [43], [48], [50], LCD [29], [45], [47], non-discriminated screen [26]–[28], [31], computer monitor [42], non-discriminated monitor [37], [40], [49], projector [51], and video display [33]. Four studies used HMD [34], [39]–[41], one of which discriminated it as being the Virtual Research V6 HMD [39]. Two studies propose a combination of three connected screens [44] or projectors [49].

Thirteen studies provided auditory cues through TV screen [24], [25], [36], [38], [43], [48], [50], LCD [45], [47], computer monitor [42], and non-discriminated monitor [32], [35], [46], all with built-in speakers. Five studies used external sound devices, such as loudspeakers [26], [27], speakers [33], 3D auditory outputs [44], and a sound system [49]. Three studies used HMD with built-in headphones [39]–[41]. The remaining seven studies do not report auditory cues [28]–[31], [34], [37], [51].

2.2.2 Sensor integration

Most studies propose VR-tools with integrated sensors that allow patients to interact with the virtual environment and receive real-time feedback of their movements. Four studies do not mention sensor integration [26], [27], [40], [41].

Fifteen studies used a camera and four of them with reflective markers. One study utilized two OptiTrack FLEX:C120 cameras (NaturalPoint, OR) belonging to the BioTrak VR system to estimate the 3D position of two markers fixed to the participant's insteps [33]. Eight studies used an infrared camera: one from Balance Control Trainer (BCT) system to measure the four markers' position on the knee [31], and six studies used the Kinect sensor (also works as Red-Green-Blue [RGB] camera) into the Xbox system to monitor the patient's COM (unique position where the sum of the weighted position vectors of all the parts of a system is equal to zero) [31], [32], [41], [43], [46], [47]. Mazzini et al. [49] used six infrared cameras from the Stability and Balance Learning Environment system (Motekforce Medical, Amsterdam, Netherlands). Two studies utilized a camera from the IREX system (Vivid group, Toronto, Canada), which determines the markers' position of cyber gloves [30], [37]. One study used a web video camera from

the SeeMe system (Brontes Processing, Gliwice, Poland) that captures the user's movements [48]. Xu et al. [46] involved the PrimeSense 3D Awareness Sensor (Apple Inc, USA) that provides gesture and skeleton tracking. Two studies employed a non-discriminated camera [29], [39] that records the leg and foot movements. Jaffe et al. [39] also used flat foot switches to detect collisions.

Seven studies used a balance board that measures, in real-time, the patient's center of pressure (COP) (point of application of the ground reaction force vector). Six of the boards belong to the Nintendo Wii Fit [3], [10], [13], [22], [27], [31] and the other is included in the BalPro system (Man&Tel, Gumi, Korea) [28]. This last study also utilized a tilting sensor that estimates the knee joint angle [28]. Mazzini et al. [49] used a force platform, included in the Stability and Balance Learning Environment system, with the purpose of measuring the patient's COP. Lee et al. [31] used two electronic scales included in BCT system. In another study, these authors [32] used a platform belonging to the BioRescue system (RM Ingénierie, Rodez, France) to monitor the patient's COP. One study employed the Tetra-ataxiometric posturography (Tetrax) (Sunlight Medical Ltd., Ramat Gan, Israel) that measures postural sway using the change in weight burden onto each of four force plates included in the system [37]. One study used the Stewart platform included in the Rutgers Ankle Rehabilitation System to determine the ankle angle [42]. Yang et al. [44] used an electromagnetic system (Fastrack, Polhemus), which tracks leg motion. Park et al. [34] used a non-discriminated sensor that measures the patient's movement.

2.2.3 Motor tasks

Looking at Table 2.1, it is possible to verify that VR-based tools comprise different motor tasks for balance rehabilitation, namely: weight shifting/bearing (9 studies), walking (7 studies), stepping (6 studies), specific-body movement at pelvic/hip (6 studies: 4 standing [1 with a harness], 1 sitting, and 1 sitting and in supine position), knee (6 studies: 5 standing [3 with and 2 without harness] and 1 not mentioned), feet (4 studies: 2 sitting, 1 standing with a harness, and 1 not mentioned), trunk (3 studies: 2 standing [1 with a harness], 1 sitting, and 1 not mentioned), arms/hands (2 studies), and standing on a single leg (2 studies). Non-discriminated aerobic exercises, reaching exercise, upper extremity movement, sit-to-stand, squats, dodging left and right, ducking, and jumping are referred in single studies. Fifteen studies combined more than one motor task [28]–[32], [34], [35], [39], [42], [45]–[47], [49]–[51] and four studies did not mention any motor task [24], [25], [38], [43].

Seven studies addressed walking, all of them on the treadmill [26], [27], [39]–[41], [44], [48]. Five of them applied different speeds according to the patient's evolution [26], [27], [40], [41], [44], and only one study varied the slope in conjunction with the virtual environment [44]. Six studies addressed stepping

[30], [33], [39], [47], [49], [50]. Nine studies addressed weight shifting in the horizontal direction [28], [31], [32], vertical direction [31], [32], and non-discriminated direction [30], [35], [36], [47], [49], [51]. Two studies tackled weight-bearing training [34], [35]. Rajaratnam et al. [36] issued COM change in sitting and standing positions.

Six studies addressed pelvic/hip movement [29], [30], [34], [35], [46], [50] including pelvic tilt in supine and sitting position [34], hip abduction [29], [35], [50], adduction [29], flexion [35], [46], extension [46], and external-internal rotation [35]. Six studies addressed knee movement [28], [30], [31], [35], [46], [49] focused on knee flexion [28], [31], [35], [46], [49] and extension [31], [35], [46], [49]. Three studies tackled trunk movement [30], [34], [35]. Park et al. [34] mentioned maintenance of trunk stability in supine and standing positions and trunk upright control in sitting position. In another study, these authors exploited trunk rotation [35]. Four studies addressed feet movement [29], [30], [35], [42], tackling dorsiflexion and plantarflexion [29], [35], [42], adduction and abduction [29], and inversion and eversion [42]. Two studies addressed arms/hands movements [49], [50], including arm circles [50]. Park et al. [34] also addressed lower extremity muscle strengthening exercises and upper extremity active movement.

IREX VR system includes five tasks for moving COP [37]. Tetrax system enables left-right and anterior-posterior weight shifting and weight-bearing [37], [52]. Nintendo Wii Fit system, in [24], [25], [38], [43], [51] includes balancing on one leg, leaning, rotating, and moving body to a rhythm [53].

2.2.4 Virtual challenges and control strategies

Virtual challenges are intended as tasks taking place in virtual environments controlled to work as serious games.

In [26], [27], post-stroke patients walked on a treadmill while an unsynchronized real-world video recording plays, depicting a sunny or rainy 400-m walking track, a 400-m walking track with obstacles, daytime or night-time walks in a community, or walking on trails. Similarly, VR-based tools from [40] and [41] simulate a park scroll and street walking, respectively. However, in [41], the optic flow speed is configured according to the 10-m walking test. Yang et al. [44] presented a virtual environment simulating the following scenarios from a typical community in Taipei: lane walking, street crossing, obstacles striding across, and park scroll. The patients are encouraged to uphill and downhill walking (treadmill slope was enabled), fast walking, and step over obstacles while walking on an unsynchronized treadmill. The patients' leg motions were tracked during the obstacles striding across the scenario for providing auditory feedback when detecting collisions with the virtual obstacles. In all the above studies, if the patient was

able to walk stably for more than 20 seconds, the treadmill speed was increased by 0.1 km/h, every 20 seconds [40], [41] and 5 % during the subsequent training session [26], [27], [44].

In [39], patients were instructed to step over ten identical stationary virtual obstacles while walking on the treadmill. They received real-time visual feedback of their legs' lateral view and vibrotactile and short sound auditory feedback when a collision with the virtual obstacle occurs (measured when the foot should not be on the ground). The virtual environment from [33] represents the patients' feet with two shoes mimicking their real movement through the positions of the markers placed on each foot. The patients are encouraged to stepping by reaching with one foot the items that rose from the ground while maintaining the other foot within a circle.

In [48], the patients walked at the same speed while training with three VR games: Ball Game, Reactive Boxing, and Cleaning Windows, included in the SeeMe system. In the Ball Game, patients are instructed to strike virtual balls with their upper extremity and avoid possible virtual shoes that can appear randomly from different directions. In Reactive Boxing, the users must touch the virtual boxes, that appear randomly on both sides of the screen, within a specific period. In Cleaning Windows game, the participants were required to clean a series of windows, as quickly as possible, by wiping off the virtual dirt that covered the windows. The users' movements were tracked by a web video camera, allowing the interaction with the VRE.

Study [29] asked for the patients to observe the real-time movements of the unaffected limb on the monitor and mimic these movements with the affected limb while sitting on a mat without back support. Similarly, in [34], the patients observe in real-time their posture and movement, and they are encouraged to mimic a pre-recorded reference motion.

In [28], the patient's COP and knee flexion are traduced into a horizontal and vertical hand-shaped cursor movement on a screen, respectively. The patients are encouraged to perform weight shifting and knee flexion/extension by moving the screen's cursor to catch fruits (Fruit-Harvesting game). Similarly, in [31], the patients move horizontally and vertically a virtual eraser according to the measurements of electronic scales and position of the markers placed on the knee, respectively. The virtual challenge consists of achieving the maximum score, defined as the percentage of the board cleaned in 2 min (Board Cleaner Game).

In [42], the patients are encouraged to perform ankle movements while sitting to navigate a virtual plane or a boat towards a series of targets according to ankle joint angle.

Lee et al. [32] controlled the virtual environments using patients' COP and encourage patients' weight shifting during the following games: City Walking (left-right shifting), Hot Air Balloon (up-down

shifting), and Bubble (total shifting). The IREX VR system, in [30], comprises the following games: Stepping up/down, Sharkbait, and Snowboard, which encourages patients' weight shifting, stepping, trunk, pelvis/hip, knee, and ankle movements. In [37], the IREX VR games are not specified. In both studies, patients are reflected on the screen, interacting with the virtual environment according to the markers' position from the glove and patients' COP. In [37], Tetrax games are also not specified, but according to another study [52], the Tetrax system comprises the following games: Catch, Skyball, Tag, Gotcha, Speedball, Immobilizer, Target, and Freeze, which encourage the patients to move accordingly to the COP.

The Xbox Kinect system, used in [35], [36], [45] includes the following games: Boxing, Table Tennis, Soccer, Golf, Ski, Football, 20 000 Leaks, River Rush, and Reflex Ridge, which recognize patients' COM. During Boxing, the patients are encouraged to punch virtual objects by moving their arms. In Table Tennis, Soccer, and Golf, the patients must hit a virtual ball with a virtual racket, kick a virtual ball, and put virtual balls in virtual golf holes, respectively. During Ski, the users must avoid the virtual barriers and follow the slope by shifting their weight. In Football game, the patients are encouraged to run with a virtual ball, avoiding the virtual opponent players. In 20 000 Leaks game, the patients must use their body's movement to stop leaking water as it spills through the tank walls in the game. In the two-players game River Rush, the patients must control the raft, while rushing down a river by moving their body from side to side or jumping to avoid obstacles. In Reflex Ridge, the patients are also encouraged to avoid obstacles by dodging left and right, ducking, or jumping over hazards as they spring forward.

The Nintendo Wii system, in [24], [25], [36], [38], [43], [51], comprises the following games: Soccer Heading, Ski Slalom, Balance Bubble, Hula Hoop, Ski Jump, Table Tiling, Penguin Slide (included in the Nintendo Wii Fit, using a balance board that recognizes patients' COP) [24], [25], [36], [38], [43], Boxing, Bowling, Snowboarding, Swimming, and Tennis (included in the Nintendo Wii Sports, using a Kinect sensor that recognizes patients' body movement) [51]. Soccer Heading game encourages the patients to reach virtual balls flying at them and to avoid other flying objects such as cleats and panda heads. In Balance Bubble game, the patients try to avoid virtual obstacles such as walls, rocks, and bees, while going down a virtual river. During Hula Hoop, Penguin Slide, Table Tilting, Boxing, Bowling, and Tennis, the players must catch virtual bows, virtual fish that comes off the water, tilt virtual balls into holes, hit the opponent towards knocking her/him on the ground, knock down virtual pins with a virtual ball, and hit a virtual ball with a virtual racket, respectively. When performing Ski Slalom (or Snowboarding) and Ski Jump, the patients are encouraged to navigate following virtual flags and to jump off a virtual hill, respectively. Swimming game encourages the patients to simulate swimming exercises with Wii remotes.

Xu et al. [46] developed a depth camera-based task-specific game called Stomp Joy, where patients are encouraged to stand on a single leg for stepping on gophers, performing hip and knee flexion or extension to control the size and falling of a footprint, respectively. The footprint changes to pink from white, and a gong sound plays if the joint angles meet the requirements. In the opposite case, a mocking sound is reproduced.

Cikajlo et al. [47] designed and developed a Rehabilitation Wayout in Responsive Home Environments – REWIRE system, consisting on three VR games: Animal Hurdler, Fruit Catcher, and Horse Runner, recognizing patients' COP and COM through the Wii Fit balance board and the Kinect sensor, respectively. In Animal Hurdler game, the patients are encouraged to step over small creatures approaching by raising a foot (standing on a single leg). In Fruit Catcher game, the patients must catch fruits and avoid chocolate eggs falling from the trees by performing weight shifting and stepping. In the Horse Runner, the patients must drive a horse that runs in the woods avoiding hitting the branches with the avatar's head by performing squats. Standing up makes the horse to run faster and the user receives bonus scores as floating honey jars.

In [49], Mazzini et al. proposed the Stability and Balance Learning Environment composed of eight VR games. The games were divided into two blocks of sessions: odd sessions that include Balloon Pop, City Ride, Hit the Mole, and 2D Maze, and even sessions that include Road Encounters, Road Stepping, Paper Flight, and Hit Knees. In the Balloon Pop and Hit Knees, the patients must burst the largest number of balloons and hit spheres that appear in a semi-circle on the screen, respectively, by performing hands' movements and, only in Hit Knees game, knee flexion and extension. In Road Encounters and Road Stepping, the patients are encouraged to hit the largest number of birds that appear on the screen by moving their hands, while automatically transverses a road, and while move the avatar using the frequency of movements of stationary march, respectively. In City Ride, 2D Maze, and Paper Flight, the patients must drive a car in a city avoiding collisions with other vehicles, drive a red ball through a labyrinth aiming to complete the course and avoiding collisions with the walls, and drive a paper airplane through a tunnel to pass as many as possible inside the narrower rings, respectively. In Hit the Mole game, the patients are encouraged to perform stepping on the force platform to hit with a hammer the moles that arise from one of the four burrows. The interaction between the users and the VRE was provided by a force platform and infrared cameras, measuring the patients' COP and the position of reflective markers placed on the patients' hands.

Sheehy et al. [50] used a Kinect camera that captures the participants' movements allowing to control an avatar. This study includes several games and activities to train subjects in standing balance

(e.g., moving a ball along maze, and Slalom Skiing), reaching (e.g., putting dishes away), stepping (e.g., stepping onto tablets placed in a circle, and Whack-a-Mole), gentle strengthening (e.g., standing hip abduction, arm circles, and sit-to-stand), and aerobic exercises (e.g., marching on the spot).

2.2.5 Clinical outcomes

The clinical outcomes are performed by a physiotherapist to record a clinical profile of the patient before or after a rehabilitation session to follow the evolution of patients' performance during the recovery process.

Table 2.1 shows that some clinical outcomes are addressed in multiple studies, namely: Berg Balance Scale (BBS: static and dynamic balance excluding walking) (22 studies [20]–[29], [31]–[34], [38], [39], [41], [42], [44]–[47]), Timed Up and Go Test (TUG: dynamic balance including walking) (18 studies [20]–[25], [27], [28], [31], [32], [34], [36], [37], [41], [43]–[46]), 10-meter Walking Test (10 mWT: functional mobility and vestibular function) (11 studies [25]–[27], [29]–[31], [37]–[39], [43]–[45]), 6-minute Walking Test (6 mWT: aerobic capacity and endurance) (5 studies [28], [39], [41], [42], [49]), Functional Reach Test (FRT: dynamic balance during maximal forward reach) (5 studies [29], [36], [38], [41], [48]), Activities-specific Balance scale (ABC: confidence during ambulation) (4 studies [38], [40], [44], [48]), Functional Ambulation Category (FAC: walking on stairs and level ground) (3 studies [28], [31], [43]), Lower Extremity Fugl-Meyer Assessment (FMA-LE: motor and sensory functions, balance, joint range of motion and pain) (3 studies [35], [42], [46]), Functional Independence Measure (FIM: independence for self-care, transfers, locomotion, communication, and social cognition) (2 studies [24], [51]), Modified Barthel Index (MBI: functional independence during ADLs) (2 studies [36], [46]), Korean version of Modified Barthel Index (K-MBI) (2 studies [28], [31]), Manual Muscle Test (MMT: muscle strength during knee extension) (2 studies [28], [31]), Tinetti Performance-Oriented Mobility Assessment (POMA: balance and stability during ADLs) (2 studies [33], [39]), and Stroke Impact Scale (SIS: disability and health-related quality of life) (2 studies [49], [50]).

Single studies also referred Barthel Index (BI) [43], Balance Performance Monitor (BPM: static and dynamic balance) [30], Modified Motor Assessment Scale (MMAS) [30], Brunel Balance Assessment (BBA) [33], Dynamic Gait Index (DGI: ability to control balance while walking in the presence of external demands) [38], Frenchay Activity Index (FAI: instrumental ADLs that patients have undertaken in the recent past) [38], Physical Performance Test (PPT: physical function while performing ADLs) [39], 7-meter walkway [42], Four Step Square Test (FSST: stepping over objects sideways, forward, and backward) [47], Standing on the left leg (STOLL) [47], Standing on the right leg (STORL) [47], Romberg's

Test (RT: vision, proprioception, and vestibular sensory function while balancing) [47], sharpened Romberg's Test (sRT) [47], Lateral Reach Test Left/Right (LRT-L/R: similar to FRT but with maximal lateral reach) [48], Clinical Test for Sensory Interaction in Balance (CTSIB: postural control) [47], Montreal Cognitive Assessment (MoCA: attention, concentration, executive functions, memory, language, constructional visual skills, conceptual thinking, calculations, and logical reasoning) [49], Five Times Sit-to-Stand Test (FTSST) [50], Community Balance and Mobility Scale (CB&M) [50], Reintegration to Normal Living Index (RNLI: degree of reintegration back into normal social activities after illness) [50], and Walking Ability Questionnaire (WAQ: mobility at home and community) [44].

2.3 Discussion

Most of the reviewed studies used a single screen. This preference can be explained once a screen is generally a cost-effective solution for a VR-based tool when compared to multiple screens and even more an HMD. Moreover, in opposition to an HMD, the screen allows the physiotherapists to follow in real-time the patients' performance during the balance training and, consequently, efficiently provide additional support to patients [54]. However, the combination of screens and HMD provides greater immersion in the virtual environment than the screens. The full immersion in the virtual environment promotes patients' concentration, involvement, and active participation in balance training, leading to an efficient recovery [55]. Furthermore, in opposition to the screens, the HMD is a wearable setup device. Despite the promising potentialities of HMD, only four studies have involved this technology. Moreover, some studies described the use of auditory (mainly) [3], [8]–[10], [13], [14], [18], [19], [21], [22], [24]–[34] and vibrotactile cues [39], filling the gap of auditory and haptic interaction, respectively, with the virtual environment.

Most of the VR-based tools include sensors to provide real-time feedback of patients' movements and to allow the patients to effectively interact with the virtual environment. Those who did not mention the use of sensors [26], [27], [40], [41] only use VR technology to develop unsynchronized virtual environments. Most of the reviewed studies used a camera or a balance board/platform as sensors. They have a promising impact in balance training once they provide an objective assessment of patients' position, posture, COM, and movement in the case of a camera and patients' COP in the case of a balance board/platform. However, both cameras and balance boards/platforms are non-wearable, limiting the VR tools to clinical practice to an indoor fixed facility.

VR-based tools were exploited to guide the execution of different motor tasks, including walking, stepping, weight shifting/bearing, pelvic/hip, knee, feet, trunk, arms/hands movement, and standing on

a single leg. Weight shifting/bearing, treadmill walking, stepping, pelvic/hip and knee movement were the most performed motor tasks, highlighting the role of both upper and lower limbs in balance control. Most studies [28]–[32], [34], [35], [39], [42], [45]–[47], [49]–[51] combined at least two motor tasks, enabling a more holistic balance training, personalized according to the patients' imminent needs and indispensable for an independent daily living [16].

Treadmill walking was mainly addressed alone in opposition to the remaining motor tasks. Moreover, the VR-based tools that encourage treadmill walking use sensors mainly to develop a virtual environment. Thus, there is space to develop VR-based tools combining walking with other motor tasks and integrating sensors to provide real-time feedback and allow patients' interaction with the virtual environment.

Most of the VR-based tools comprise a closed-loop control, providing real-time feedback according to integrated sensors' objective measures. Feedback encourages the patients to self-control their movements towards motor relearning [56]. The virtual challenges applied in closed-loop VR-based tools have no trend but are dependent on the encouraged motor task. These challenges imply the development of serious games generally aiming to catch, avoid, or navigate virtual objects, fostering patients' enthusiasm and motivation. Thus, patients are encouraged to perform implicit motor tasks to accomplish the virtual challenge, improving their balance control. Although the variety of VR-based tools found in the literature, the majority do not suggest a user-centered design, once virtual challenges were not tailored to the actual user's motor needs, which can limit the clinical outcomes. Moreover, the studies analysed generally use virtual challenges aimed at entertainment with more playful activities, with a lack of ADLs. Therefore, there is space in future research to compare the efficacy of post-stroke balance rehabilitation of VR-based tools specifically designed for this purpose with existing VR-based tools.

All the studies reported clinical outcomes, being the BBS and TUG the most used ones. They allow assessing static and dynamic balance that is usually affected after a stroke [47], [51].

2.4 Conclusions

This review focuses on the specifications of VR-based tools for post-stroke balance rehabilitation. The optimal VR tool solution should consider the requirements in terms on technology and balance rehabilitation. Thus, for the VR tool to have a user-centered design, it should consider the following technological requirements: 1) ensure wearable VR technology and biosensors in order to allow the performance of static and dynamic motor tasks; 2) identify the virtual challenges according to the user's needs in daily activities, as well as the motor tasks that should be included in them; 3) ensure multimodal feedback with visual, auditory, and vibrotactile stimuli, which does not exist in the analysed literature, and

is needed to have a more realistic experience. Attending to the requirements of balance rehabilitation, the VR tool should: 1) select the motor tasks based on the most performed tasks in the literature, as well as the tasks included in the most performed clinical scales in the literature (BBS and TUG), these being: weight-shifting, stepping, look over the shoulder, reaching, knee flexion and extension, trunk and pelvic/hip movement, standing upright on one leg, sit-to-stand and stand-to-sit, and walking; 2) assess balance using key metrics, namely the position and velocity of the COM.

3. SYSTEM DESCRIPTION: VR-BASED TOOL FOR BALANCE TRAINING

The main outcome of this dissertation is a wearable VR-based tool designed for balance training that can be useful for people with loss of balance due to age or diagnosed illnesses (e.g., stroke, cerebral palsy, Parkinson's disease). According to the conclusion of the literature review, the VR tool created should: ensure wearable VR technology, have a wearable and reliable sensor system for monitoring in ADLs, allow real-time synchronization between VR technology and sensors, and contain ADL-based virtual challenges that include motor tasks reported in the literature and clinical BBS and TUG scales. In this manner, this chapter describes the developed VR-based tool following a user-centered design, detailing the VR technology, sensor integration, motor tasks and related virtual challenges that users have to perform during VR training. The chapter ends with the strategies that were created to control the VRE, allowing users to interact with it, and provide real-time feedback about users' balance.

3.1 VR technology

The fully immersive, portable, and wearable commercial setup device of virtual reality HTC Vive Pro Full Kit (HTC VIVE Pro, HTC, Taiwan, ROC) was used in the developed VR-based tool (Figure 3.1 [57]). It is composed of a VR headset, two hand-held controllers, and two base stations for movement tracking. The headset and controllers have infrared (IR) sensors that detect the base stations' emitted IR pulses for determining the headset and controllers' current position in space. The base stations and controllers allow defining the play area (delineated between base stations using the controllers) through the "Room Setup" routine of Steam VR software. The play area (e.g., 2 m x 1.5 m, in this project) sets the virtual boundaries of Vive Pro and, as the name implies, the area where the interaction with VR objects are possible [58]. The "Room Setup" routine also calibrates the movement tracking of headset and controllers for the defined play area.



Figure 3.1 - HTC Vive Pro Full Kit composed by a VR headset, two controllers, and two base stations [57].

Some of the HTC Vive Pro system specifications are mentioned in Table 3.1 [57]. As it can be seen in Table 3.1, beyond the visual cues, the HMD can also provide auditory cues to users through the integrated headphones. The hand-held controllers allow providing vibrotactile cues to the users and their interaction with the VRE through buttons. The HTC Vive Pro system's ability to provide multimodal stimuli (visual, auditory, and vibrotactile cues) motivated its selection such that the balance training involves cues available in the real world.

Table 3.1 - Specifications of HTC Vive Pro's headset and controllers [57]

Headset Specifications	
Resolution	1440 x 1600 pixels per eye (2880 x 1600 pixels combined)
Refresh rate	90 Hz
Field of view	110 degrees
Input	Integrated microphones
Sensors	SteamVR Tracking G-sensor Gyroscope Proximity Eye Comfort Setting (IPD)
Audio	Hi-Res certificate headset Hi-Res certificate headphones (removable) High impedance headphones support
Controller Specifications	
Input	Multifunctional trackpad Grip buttons Dual-stage trigger System button Menu button
Sensors	SteamVR Tracking 2.0

Furthermore, the HTC Vive Pro has some recommended system requirements (Table 3.2) [58] that the host computer must meet to properly enjoy VIVE experience. A computer Republic of Gamers (ROG) Strix Helios [59] with a NVIDIA GeForce RTX 3080 Ti GPU [60] was used to run and connect the software needed to build the VR-based tool. According to Table 3.2, the computer ROG Strix Helios comprises all the minimum and recommended requirements to use HTC Vive system.

A monitor screen was combined with the HMD so that the VR training can be followed by other people as a physiotherapist (using "Display VR view" option of Steam VR). Thus, the physiotherapists can track in real-time the users' performance during the balance training and, consequently, they can provide

additional support by instructing efficiently the users according to their imminent needs, as mentioned in subchapter 2.2.1.

Table 3.2 - Comparison of recommended system requirements to use Vive Pro [58] and the specifications of the used computer (ROG Strix Helios) [59][60]

Component	Recommended system requirements	Computer ROG Strix Helios specifications
Processor	Intel® Core™ i5-4590/AMD FX™ 8350 equivalent or better	Intel® Core™ i9-10940X CPU 3.30GHz
GPU	NVIDIA® GeForce® GTX 1070/ Quadro P5000 equivalent or better, AMD Radeon™ Vega 56 equivalent or better	NVIDIA GeForce RTX 3080 Ti, 12.0 GB GDDR6X
Memory	4 GB RAM or more	64 GB RAM
Video output	DisplayPort 1.2 or newer	3 x DisplayPort 1.4a
USB port	1x USB 3.0 or newer	4 x USB 3.0 Gen 1, and USB 3.1 Gen 2 Type-C™
Operating system	Windows® 10	Windows 10 Pro, 64-bit

3.2 Sensor integration

The inertial measurement unit-based motion capture system MVN Awinda (Xsens, Enschede, The Netherlands) was chosen given its reliability for body motion analysis in free-living conditions. The full body suit configuration, that involves 17 wearable Wireless Motion Trackers (MTw) sensors (Figure 3.2A) fitted on the body with adjustable straps or other garments (Figure 3.2B), was used to track the kinematics of the full body during the training [61]. Each of these sensors contains 3D linear accelerometers, 3D gyroscopes, 3D magnetometers, and a barometer, providing 3D acceleration, 3D angular velocity, 3D earth magnetic field, and atmospheric pressure, respectively. The sensors also provide 3D drift-free orientation [62]. The MVN Awinda kit also contains a Awinda Station (Figure 3.2C) that controls the reception of synchronized wireless data from all these wirelessly connected MTw's [62].

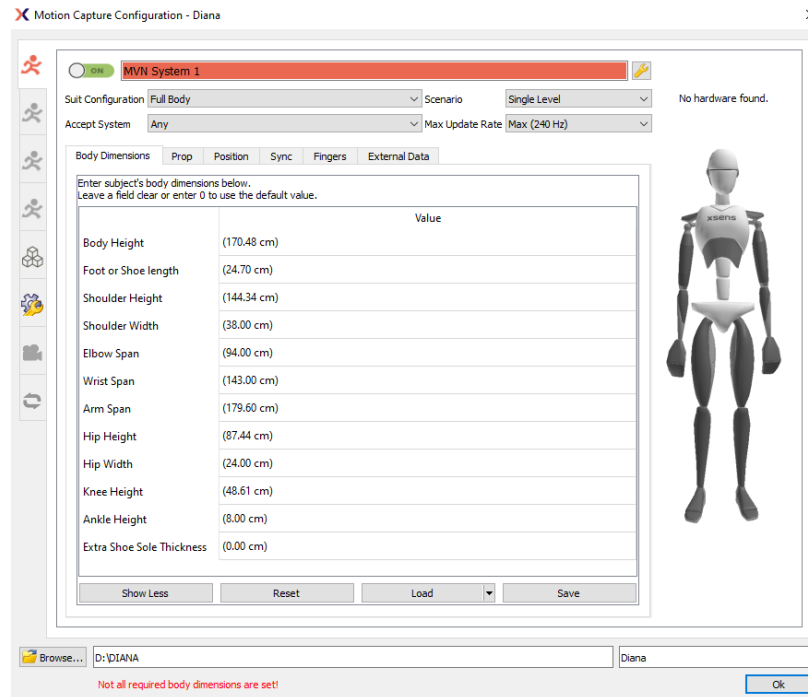


Figure 3.2 - Xsens MVN Awinda: A) MVN Wireless Motion Tracker (MTw); B) MVN Awinda MTw's position on body with adjustable straps; C) MVN Awinda station [62].

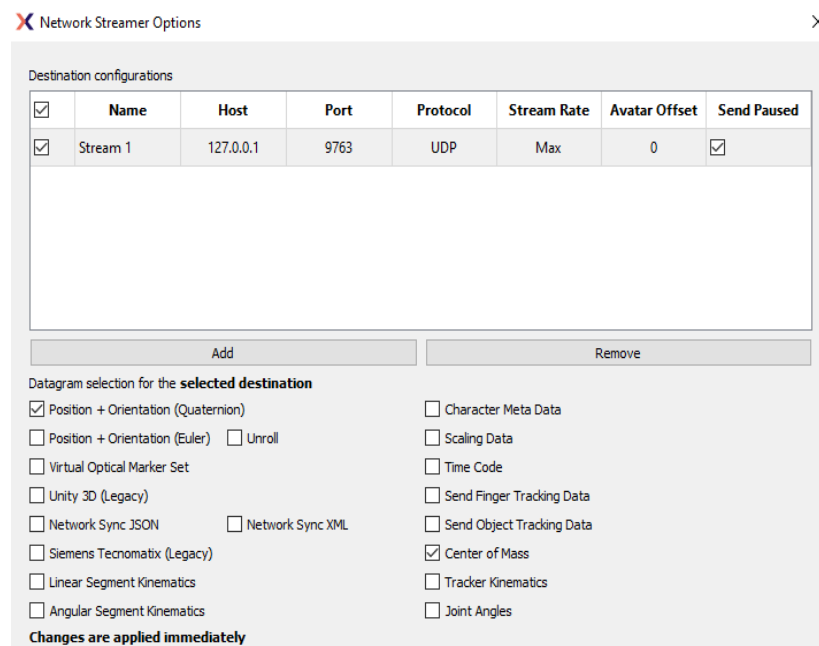
The MVN Awinda system has a large communication range (up to 50 m), not restringing the use of the hardware in the defined play area [63]. The low latency value of 30 ms makes it possible to control in real-time the movement of an avatar in a serious game. The 6 hours of battery life are sufficient for a rehabilitation session (usually last 30 and 60 minutes [64]), ensuring that the device does not discharge halfway through or before the session is over. Its portability makes the MVN Awinda ideal for training in any location (e.g., hospital, clinics, or even at home), potentiating daily practice and, thus, accelerating the recovery process.

The MVN Analyze Pro software is specialized for biomechanics, sports science, ergonomics, health, or rehabilitation purposes [61]. This software ensures real-time previewing, recording, and streaming of reliable and accurate human motion kinematics estimated from the combination of raw inertial data with a calibrated biomechanical model, as follows [62].

Firstly, the biomechanical model is scaled with user's body dimensions (Figure 3.3A), namely: body height, shoulder height, hip height, knee height, ankle height, extra shoe sole thickness, shoulder width, elbow span, wrist span, arm span, hip width, and foot or shoe length. All the dimensions were measured according to the MVN User Manual [62], with a duration of 6 minutes (value obtained in empirical tests with healthy subjects). Secondly, the biomechanical model is calibrated to align the motion trackers to the subject's segments using the "Npose + Walk" routine of MVN Analyze Pro, which lasts approximately 5 minutes (value obtained in empirical tests with healthy subjects). The system also enables to perform a static calibration that can be feasible for patients with mobility deficits.



A)



B)

Figure 3.3 - MVN Analyze Pro software: A) User's body dimensions to scale the Xsens biomechanical model; B) Datagram selected.

After achieving a successfully calibration, it is possible to stream real-time data from the MVN Analyze to the third-party software used to develop the VRE. The data streaming utilizes the UDP Protocol, a unidirectional and stateless protocol that does not require the receiver to answer incoming packages, allowing for greater speed than TCP Protocol [62], [65] (Figure 3.3B). In this thesis, it was selected the

datagram options that are checked in the Figure 3.3B, namely: “Position + Orientation (Quaternion)” and “Center of Mass”. The “Position + Orientation (Quaternion)” provides the absolute positions (in meters) and orientation (in quaternion) of each body segment. The “Center of Mass” option streams the absolute 3D position of the COM. The position of body’s segments and COM are usually used for postural behaviour and balance control assessment, as proved in the literature review (chapter 2).

3.3 Motor tasks

The motor tasks addressed in the developed VRE were chosen based on the motor tasks of the studies analysed in subchapter 2.2.3 and on the most performed clinical outcomes, BBS and TUG, as concluded in subchapter 2.2.5. So, while using this VR-based tool for balance training, the users are practicing the motor tasks clinically accepted and performed in conventional physical rehabilitation, allowing to increase the tool’s acceptability. The chosen motor tasks are: walking, stepping, sit-to-stand, stand-to-sit, knee flexion and extension, weight-shifting, trunk and pelvic/hip movement, look over the shoulder, standing upright on one leg, and reaching.

3.4 Virtual challenges and VRE

The virtual challenges comprise ADLs to complement the physical training with functional training towards enhancing the balance function of patients while performing their daily challenges. Further, as these activities are usually executed, they are the main reason for falls, being important to train these activities in order to decrease the patient’s fall risk and improve their confidence and quality of life [66]. Thus, during VR training, users can practice their routine that is essential for their minimal independence, such as basic hygiene care, transfer, ambulation, or other activities performed at home [67]. Four virtual challenges were proposed - Fruit Catcher, Cooking, Take a Shower, and Watch TV. These challenges involve the nine motor tasks mentioned in the above subsection, as detailed in Table 3.3.

Table 3.3 - Virtual challenges and respective motor tasks

Motor tasks	Virtual challenges			
	Fruit Catcher	Cooking	Take a Shower	Watch TV
Walking				x
Stepping	x			
Sit-to-stand and stand-to-sit				x
Knee flexion and extension		x	x	
Weight shifting	x	x		
Trunk and pelvic /hip movement		x		
Look over the shoulders	x			
Stand upright on one leg			x	
Reaching	x			

The real-time development 3D platform Unity, created by Unity Technologies (Copenhagen, Denmark), with Editor version 2019.4.29f1 and Unity Hub 2.4.2 version, was used to create and develop the four 3D virtual challenges and all the surrounding VRE. It consists of a house with detailed indoor and outdoor spaces designed to be the most realistic and immersive as possible so that the users train according to their real needs and focus on the enthusiastic virtual challenge, respectively. To fulfil these purposes, in addition to the objects downloaded to fill the space and make it as welcome and real as possible, natural ambient sound and ambient sunlight were also created and designed to change the volume audio (low and high) and intensity of light (higher and lower) depending on whether the user is indoors or outdoors, respectively. Furthermore, the interior of the house was illuminated with the light from the sun coming through the windows without the need for light from lamps. In the remaining

subchapter, the four virtual challenges will be described (their main virtual goals and how to achieve them by practicing the related motor tasks) as well as their respective surrounding VRE.

Fruit Catcher

For the Fruit Catcher virtual challenge, it was created a backyard at the back of the house. In addition to the surrounding VRE (Figure 3.4), the backyard has a tree, a ladder, and apples as main virtual objects to carry out the virtual game (Figure 3.5).

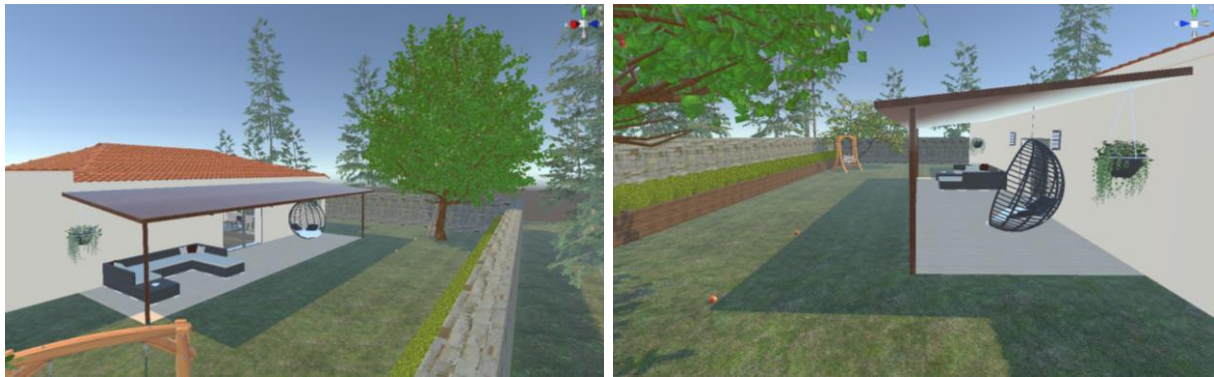


Figure 3.4 - House backyard design.



Figure 3.5 - Apple tree with the ladder.

The Fruit Catcher game aims that the user: 1) climbs six steps of the ladder perched on the tree through stepping with each foot alternately; and 2) reach and catch nine apples, three forwards and three to each side (left and right), by performing weight shifting (with their feet together and without moving them) and looking forwards and over the left and right shoulders, respectively. The nine apples were placed at predefined distances (5 cm, 12.5 cm, and 25 cm after the hand position with arms

outstretched, of a person with 1.70 m height) corresponding to the second, third, and fourth levels of the eighth BBS' task (entitled "Reaching forward with outstretched arm while standing"), respectively.

Cooking

For the Cooking virtual challenge, a kitchen division in the house was created, with furniture, dishes, fridge, stove, and other electrical equipment (Figure 3.6). The four shelves full of food products (Figure 3.7) are the main virtual objects to carry out this virtual game.



Figure 3.6 - Kitchen division design.

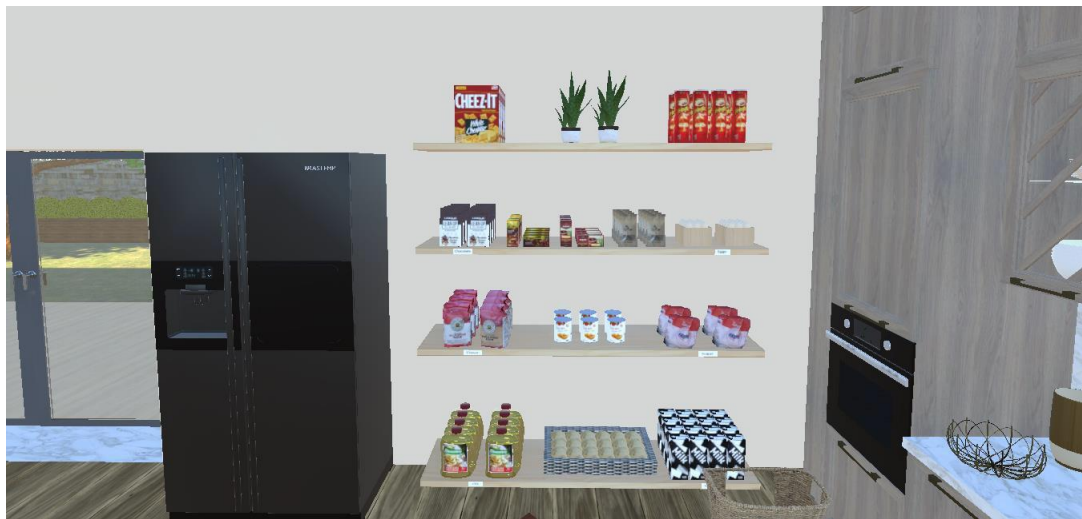


Figure 3.7 - Kitchen shelves.

The Cooking game aims that the user, with their feet together and without moving them, reaches the ingredients (selected to make a cake) at specific points of the shelves: 1) three levels of height adjusted according to user's height (2 ingredients/level) through knee and hip flexion and extension, respectively; 2) and, on the left and right sides (3 ingredients/side) by performing weight shifting. The user should grab one of each of the ingredients tagged with labels (chocolate, eggs, flour, sugar, oil, and milk) and put them in the basket beside her/him, maintaining her/his balance. This virtual challenge was based on the activity of cooking, which is very often performed in a daily basis.

Take a Shower

For the Take a Shower virtual challenge, a bathroom division was created in the house. In addition to the surrounding environment (Figure 3.8), a bathtub with a height of 40 cm (standard height of an undermount real bathtub [68]) (Figure 3.9) was implemented as being the main virtual object to carry out this game.

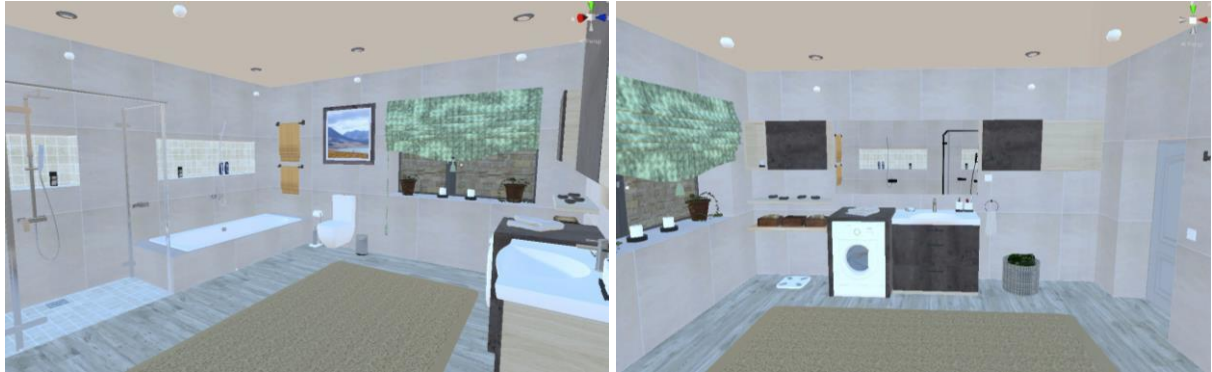


Figure 3.8 - Bathroom division design.



Figure 3.9 - Bathtub used in the "Take a Shower" game.

The Take a Shower game aims that the user: 1) enters the bathtub with one foot at a time through knee flexion and extension without listening a sound of a kicking that is generated every time she/he touches the bathtub's rim; 2) once inside the bathtub, stands upright on one leg, for listening to a sound of running water (auditory feedback) in case of success in lifting the leg enough, mimicking that she/he is washing her/himself. The user must lift the leg at least 25 cm and stand upright on one leg for at least 10 s (time to reach the maximum score on fourteenth BBS's task: standing on one leg) to achieve the maximum score. This virtual challenge was based on the ADL of taking a bath, as it is an activity that is often performed and with a higher risk of falling. Thus, the motor task of getting into the bath and, inside

the bathtub, having some balance (e.g., when lifting one leg to wash it) should be trained so as not to fall in it.

Watch Tv

For the Watch Tv virtual challenge, a living room division in the house was created with a surrounding environment decorated as real as possible (Figure 3.10) and with special emphasis on the television and the sofa once they are the main virtual objects to carry out this game. The sofa was designed with a height of 47 cm according to the standards of real chairs [69].



Figure 3.10 - Living room division design.

The Watch Tv game was inspired by the TUG clinical test. In this game, the user, initially raised, must: 1) sit in the virtual sofa (supported by a real matched chair); 2) stand; 3) walk 3 meters forward towards the television until it turns on; 4) rotate 180 degrees; 5) walk again 3 meters towards the sofa, ending the game. A video of nature with sound incorporated (visual and auditory feedback) plays on the television when the user reaches the 3 meters forward the sofa. The sit-to-stand and stand-to-sit tasks are performed in a different order when compared to the real TUG to ensure the user's safety by matching the position of the real chair with the virtual sofa.

3.5 Control strategies

This thesis developed control strategies to create a dynamic virtual environment that allows the users to interact with it and receive feedback, potentiating users' motivation and participation during training and, thus, accelerating the recovery process. An avatar mimicking in real-time the user's body movement was inserted in all the serious games, so that the virtual challenge seems realistic, and the user feels a high sense of presence in the VRE. Furthermore, the provided feedback (visual, auditory, or vibrotactile) allows the users to follow in real-time their postural control and to understand if the virtual challenge was successfully accomplished or not.

Feedback on balance indicators is relevant for postural control. Balance is maintained by regulating the interactions between the COM and base of support (BOS) [70]. In a brief description, in the context of defined motor tasks, the BOS is the area that includes every point of contact (one or both feet) that the person makes with the supporting surface (floor) and, in the case of having more than one point contact (both feet), the area between them too. The COM is the unique position where the sum of the weighted position vectors of all the parts of a system is equal to zero. Stable gait and balance are achieved if the COM representation on the supporting surface is within the BOS, being the limits of the BOS considered the limits of a stable balance [70]. For all the virtual challenges, in addition to a first-person view, the user has access to a second real-time view regarding her/his COM projected on her/his feet.

3.5.1 First and second person views

MVN Live Animation is a module, imported from the Unity Asset Store, in Unity software, that allows Unity developers to receive, process, and view Xsens live motions on an avatar (from “MvnPuppet” Prefab, Figure 3.11) [71]. The avatar is formed by 23 linked segments that move according to real-time streamed data (through the configuration of the Network Streamer mentioned in the subchapter 3.2) from MVN Analyze, mimicking the user’s movement.

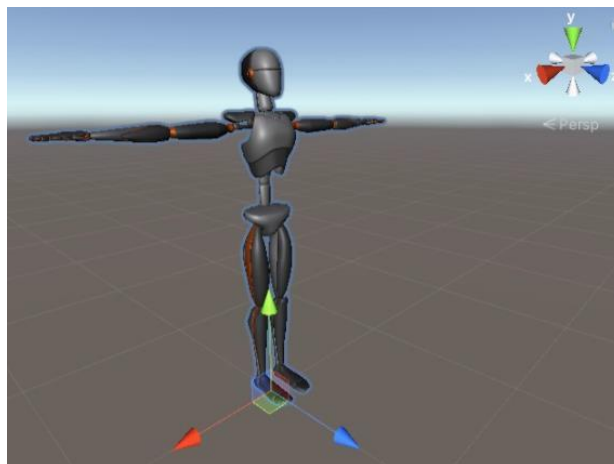


Figure 3.11 - Mvn avatar facing the Z-axis in Unity environment [71].

The first-person perspective was provided to allow high immersion, giving the user a sense of presence in the VRE, once she/he can interact with the virtual objects having a similar perspective to the one in the real world. This perspective was implemented by disabling the position tracking from the headset and controllers ("Track Pose Driver") and inserting and adjusting them on avatar’s head ("Head_End") and hands ("LeftCarpus 1" and "RightCarpus 1"), respectively. In this manner, the play

area moves according to the user's motion in position and rotation (measured by Xsens sensors), allowing to control the inputs and outputs from headset and controllers.

A second-person perspective view was created so that users can perform the virtual challenges and easily look at her/his feet with the COM projected. Therefore, this view shows the image provided by a camera pointed to the avatar's feet (and that moves according to it, displaying the feet always pointing forward), providing visual feedback in real-time of simultaneously the user's COM and BOS (defined by the area delimited by the feet on ground [70]). Moreover, the second-person view was associated with a plane that moves according to the avatar's head so that, wherever the user looks, she/he can follow her/his BOS and projected COM, being able to adjust her/his posture during the practice of any virtual challenge towards maintaining balance and preventing her/him from falling. A representation of the COM (one red ball with a diameter of 1 cm) was implemented and placed at feet level to easily visualize if the COM is within the BOS. The position of the virtual red ball was controlled according to the streamed COM data (from MVN Analyze) post-transformed from the MVN reference axis to the Unity reference axis.



Figure 3.12 – Watch Tv virtual challenge: A) In first person view; B) In first person view, with the second real-time view (highlighted by the orange square).

3.5.2 Grab motion

Both the apples on the tree and the food placed on the shelves (Fruit Catcher and Cooking games, respectively) are reached and caught using the HTC controllers. This control strategy allows the user to grab objects as long as they are not static objects and have physical properties. This function was

associated to both left and right controllers' Trigger button by configuring "Open binding UI" to add "Grab" action on "SteamVR Input" (Figure 3.13 [72]).

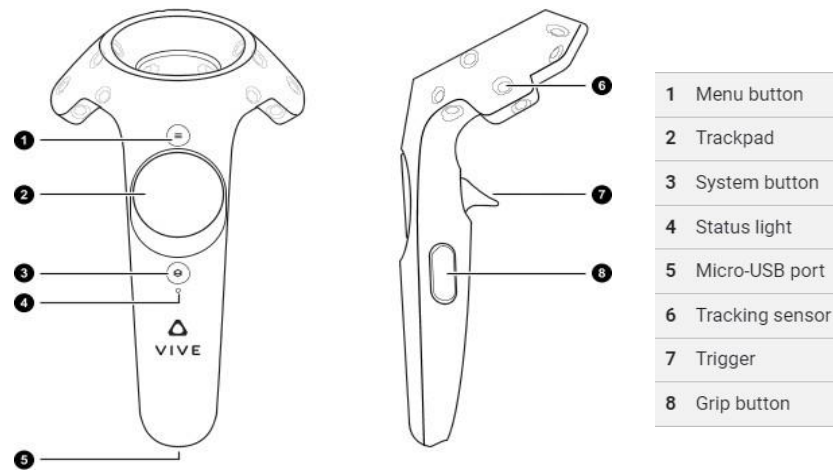


Figure 3.13 - HTC controllers' buttons and respective caption [72].

3.5.3 Vibrotactile feedback

Vibration was enabled in the HTC controllers to increase the immersion of the user during two situations: 1) when grabbing; 2) and colliding with virtual objects.

This first situation was associated to both left and right controllers by configuring "Open binding UI" to add "Haptic" action associated with Trigger button. The haptic amplitude, duration, and frequency were set to 100 g, 0.4 s, and 22 Hz, respectively, when grabbing virtual objects). The second situation occurs when the controllers collide with virtual objects by enabling the controllers' and virtual objects' "Box Colliders" and "OnTriggerEnter" components. In this sense, every time a collider from a virtual object enters the controllers' trigger, vibration is enabled (only in the controller that touches the virtual objects) with haptic amplitude, duration, and frequency of 88 g, 0.4 s, and 22 Hz, respectively, mimicking the sensation of hitting real objects with the hands. The amplitude, duration, and frequency values for two situations were selected in empirical tests with healthy subjects.

3.5.4 Visual and auditory feedback

In the Watch Tv game, a video (inserted in a Video Player component) plays when the user approaches the TV and reaches the three-meter walk and stops 90 s after being activated, giving users' interaction with the VRE, as if the user had turned the tv on. The Tv screen render texture was chosen to be the Target Texture where the video plays. The video plays showing images and sounds of nature when the avatar's collider enters de television's collider (trigger).

In the first part of the “Take a Shower” game, the user must enter the bathtub without touching the bathtub’s rim. However, a sound imitating a kick against a wall is enabled every time she/he touches it, as if she/he had really kicked the bathtub’s rim. To implement this control strategy, colliders were created both on the stone of the bathtub and on the user’s right and left feet. Whenever the collider of one of any user’s feet enter the collider of the bathtub’s rim (trigger), the sound plays, giving auditory feedback to user that she/he kicked the virtual bathtub’s rim.

In the second part of the “Take a Shower” game, a sound of running water plays if the user stands upright on one leg inside the bathtub, as if she/he was washing the leg. The sound plays while the height of user’s foot (any foot) is above 25 cm from floor and stops 10 s after it starts (according to the fourteenth BBS’ task: “Standing on one leg”) or if the user puts the height of her/his foot below 25 cm from the floor. The height of the feet is assessed through “Position + Orientation (Quaternion)” streamed data from MVN Analyze.

3.5.5 Stepping up the ladder

In the first part of the “Fruit Catcher” game, the user must climb the ladder perched in the tree by stepping one leg at a time. To develop this control strategy, the vertical and horizontal position of the avatar moves up and forward 25 cm and 4 cm (coinciding with the steps of the ladder), respectively, every time the height of any foot is above 25 cm from the floor and then backs to the floor’s height, mimicking that the user is climbing real stairs.

3.5.6 Shelves height

To make the “Cooking” virtual challenge more user-centered and thus make the difficulty level as equivalent as possible between subjects according to their anthropometric measurements, the height of the shelves was automatically customised according to the user height. This personalisation was made for three shelves at different heights: the highest at eye level, the middle one at waist level, and the lowest at ankle level.

Table 3.4 shows the height of the counter type furniture according to the users’ height. This information was used to personalise the height of the shelf at the waist level. These measures were found on a research of standard measures of kitchen shelves according to ergonomic rules [73].

Table 3.4 - Counter type furniture's height (cm) according to the user's height (cm)

User's height (cm)	Counter type furniture's height (cm)
150 - 160	70 - 85
160 - 170	85 - 95
170 - 180	90 - 105
180 - 190	95 - 110

According to ergonomic rules, the shelf placed at eye level must be between 40 cm to 70 cm (for user's height ranging from 150 cm to 190 cm, respectively) above the counter type furniture (shelf at waist level) [73]. Additionally, the shelf at ankle level must be located between 10 cm and 20 cm (foran user's height ranging from 150 cm to 190 cm, respectively) from the floor level [73]. A fourth shelf, for decorative purposes only, was added as many centimetres above the eye-level shelf as the centimetresthat the eye-level shelf is above the middle shelf.

3.6 Conclusions

The fully immersive developed VR-based tool for balance training was designed in Unity 3D software, integrating the commercial setup device of VR HTC Vive Pro Full Kit to immerse the user in the VRE and the IMU-based motion capture system Xsens MVN Awinda, in a full-body configuration, to allow the user to interact with the VRE according to her/his motion. This is a wearable setup that enables balance training both in clinical and home settings.

The VR-based tool includes four virtual challenges (corresponding to four ADLs) namely Fruit Catcher, Cooking, Take a Shower and Watch Tv, addressing a total of nine motor tasks (based on literature review, and BBS and TUG clinical tests) such as walking, stepping, sit-to-stand and stand-to-sit, knee flexion and extension, weight shifting, trunk and pelvic/hip movement, look over the shoulders, stand upright on one leg, and reach with hands as far as possible. To create the static VRE, a garden with an apple tree with a perched on it, a kitchen with shelves with food, a bathroom with a bathtub, and a living room with a sofa and a Tv were created for the Fruit Catcher, Cooking, Take a Shower, and Watch TV virtual challenges, respectively. To create a dynamic virtual environment and allow the user to interact with it and receive feedback from it, six control strategies were created, namely first and second person views, grab, vibrotactile feedback, visual and auditory feedback, stepping up the ladder, and shelves height. The tool provides visual, auditory and vibrotactile stimuli through HMD, the built-in headphones, and HTC controllers, respectively. Future work envisages the creation of an interactive menu.

4. QUESTIONNAIRE FOR USER-CENTERED DESIGN

A questionnaire to assess the most performed and appreciated ADLs requiring balance was elaborated, in parallel with the development of VR tool, to appoint guidelines for the VR-based tool to follow a user-centered design. First, the questionnaire was introduced, and its questions were listed. Then, the participants who answered the questionnaire were presented, followed by the statistical analysis performed on the data. The results are then presented and discussed, ending with a brief conclusion.

4.1 Questionnaire about ADLs requiring balance

A questionnaire about ADLs requiring balance was elaborated in Google Forms to find out if the virtual challenges created in this project are in accordance with the preferences and most performed activities of most people who answer the questionnaire. Thus, it allows to understand if the VR-based tool is tailored according to the user's needs and preferences, following a user-centered design.

The questionnaire was divided into two parts: 1) the volunteer's characteristics; 2) ADLs requiring balance. In the first part, the volunteers were asked to indicate the age and gender, and then the following questions: 1) if she/he considers her/himself as an active person; 2) if she/he has any illness or disability that prevents from being more physically active and, if yes, which illness or disability; 3) where she/he lives during most of the year (countryside, city, or other); 4) how she/he usually moves around on their daily basis (on foot, by car, public transport, or other). These questions intend to characterize the population under study, allowing to assess how these factors affect the most performed and appreciated ADLs.

Additionally, the volunteers were asked if they have or already had physiotherapy and if they felt motivated during the sessions. If not, they were asked to enunciate what were the reasons (tiring, boring, demanding, other). These questions pretend to study the population under study's opinion of conventional therapy.

In the second part of the questionnaire, volunteers were asked to indicate, from the fifteen presented ADLs, which are the five that they performed the most, and the five that they prefer to perform. By questioning this, the idea is that the VR tool, in addition to training the important ADLs to users' need (according to their most performed activities), also creates a fun experience for them (based on the activities they most enjoy doing). The fifteen possible tasks were: 1) climb the stairs of the house/building; 2) tighten the laces; 3) change burnt out light bulbs; 4) climb a tree and pick fruit; 5) watch television; 6) play cards; 7) drive a car; 8) ride a bicycle; 9) ride public transport; 10) clean the floor; 11) clean the

house windows; 12) walk a pet; 13) cook; 14) take a bath; 15) and dance. These activities were chosen because they are widely performed ADLs that involve the motor tasks reviewed in the literature and clinical scales. They were also requested to, if they have suggestions, indicate another activity that they frequently perform and another that they like to do.

4.2 Participants

There were no exclusion criteria for filling the form (younger and older subjects, healthy and injured subjects). The form was divulgated through institutional e-mail from University of Minho, being the members asked to propagate the form within family and friends. Sixty-four participants (age: 36.95 ± 19.20 years, gender: 65.60 % female and 34.40 % male) answered the questionnaire, all of whom completed it in its entirety. Of these: 1) 67.20 % consider themselves physically active; 2) 9.40 % have or had a disease that prevents them from being more active, namely stroke, Parkinson's Disease, heart disease, Meniere's syndrome, cancer, hyperthyroidism, and asthma; 3) 81.25 % live in the city and the remaining 18.75 % live in the countryside; 4) 63.75 % use motorized transport (by car or public transport) to get around in their daily lives.

4.3 Descriptive Analysis

The questionnaire about ADLs involving balance aims to improve the design of the implemented VR-based tool, making it as user-centered as possible. In this regard, it is important to understand if some factors such as: age, gender, degree of daily physical activity, health condition, degree of home urbanization, and type of transport daily used, influence the activities that the participants most perform or like to do in their daily lives. For this purpose, frequency analysis was performed. Additionally, a frequency analysis was implemented to study the population's opinion of conventional therapy.

4.4 Results

This subchapter focuses on the results of the developed questionnaire, answered by 64 subjects. Each of the following subchapters presents two graphs: 1) one allusive to the five activities that the subjects do the most; 2) and another relative to the five activities that they most like to do among fifteen activities presented in the questionnaire. Firstly, the global results are presented and, then, a study by factor is carried out to conclude about the influence of the factors on the most performed and appreciated ADLs. Also in this subchapter, the results of the questions about conventional physical therapy are presented.

4.4.1 Global results

Figure 4.1 shows the frequency count, in percentage, of the five activities that the 64 subjects most perform in their daily lives. By analysing Figure 4.1, it is possible to verify that the five tasks that people most execute are, in general, taking a shower (17.98 %), climbing the stairs in the house/building (16.09 %), watching television (14.84 %), cooking (12.62 %), and driving a car (10.73 %).

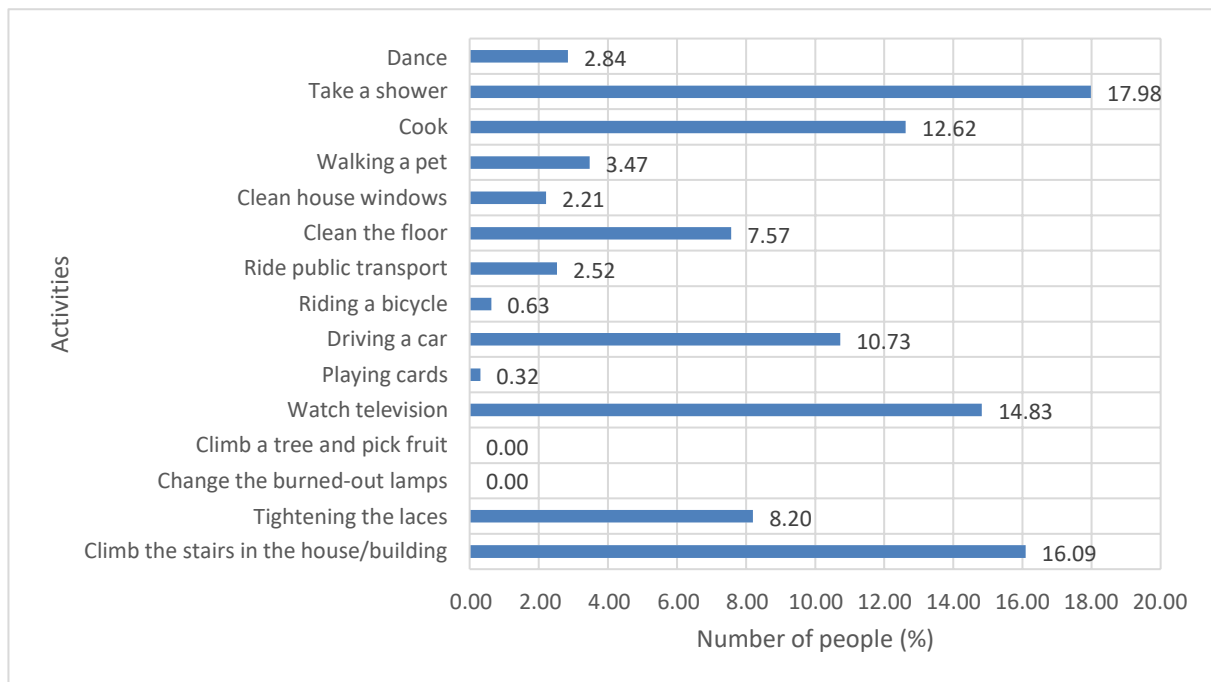


Figure 4.1 - Number of subjects, in percentage, by activity, considering the five activities, out of fifteen, that people perform the most.

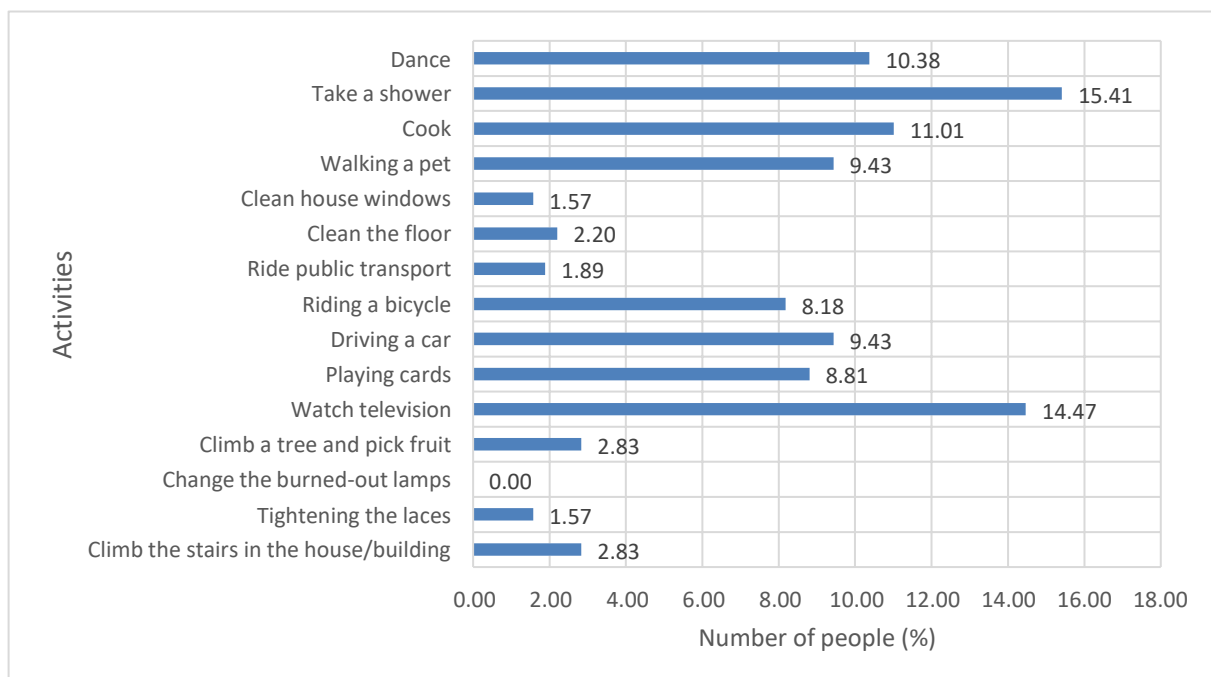


Figure 4.2 - Number of subjects, in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.

Figure 4.2 indicates the frequency of the five activities that the participants most like to do in their daily life. Taking a shower (15.41 %), watching television (14.47 %), cooking (11.01 %), dancing (10.38 %), followed by walking a pet and driving a car both with the same percentage (9.43 %) are the preferred ADLs.

4.4.2 Age

In this subchapter, the data from the questionnaire were analysed by age according to the following classes: 1) 18-40 years; 2) 40-66 years; and, 3) > 66 years. This analysis allows concluding if the age factor interferes on the people's ADLs. Since balance disorders have a higher incidence in people over 40 years, it was considered relevant to use this age value as a reference point for creating the above-mentioned classes. Another reference point used was the age of 66 years that corresponds to the age of retirement in Portugal [74]. The number of people, by age, who answered the questionnaire, are illustrated in Figure 4.3.

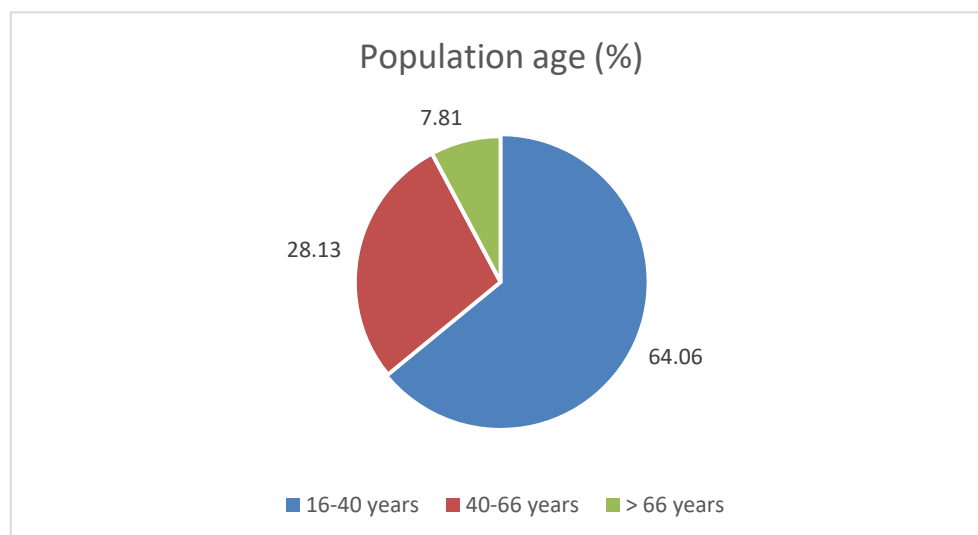


Figure 4.3 - Number of the individuals by age (16-40 years, 40-66 years, > 66 years).

The Figures 4.4 and 4.5 present the answers of the subjects by age (18-40 years, 40-66 years, and > 66 years) about the ADLs they most perform, and the activities they most enjoy doing, in their daily lives, respectively.

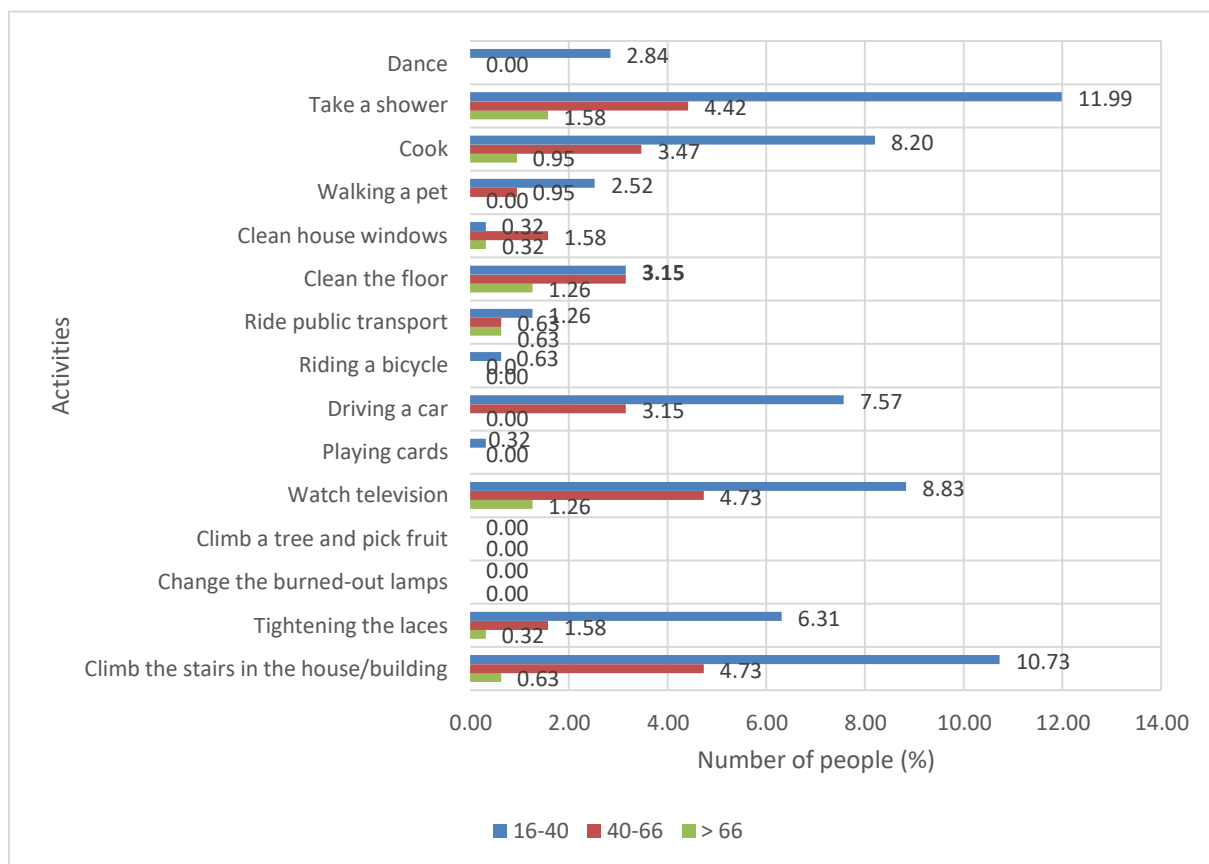


Figure 4.4 - Number of subjects by age (16-40, 40-66, > 66 years), in percentage, by activity, considering the five activities, out of fifteen, that people do the most.

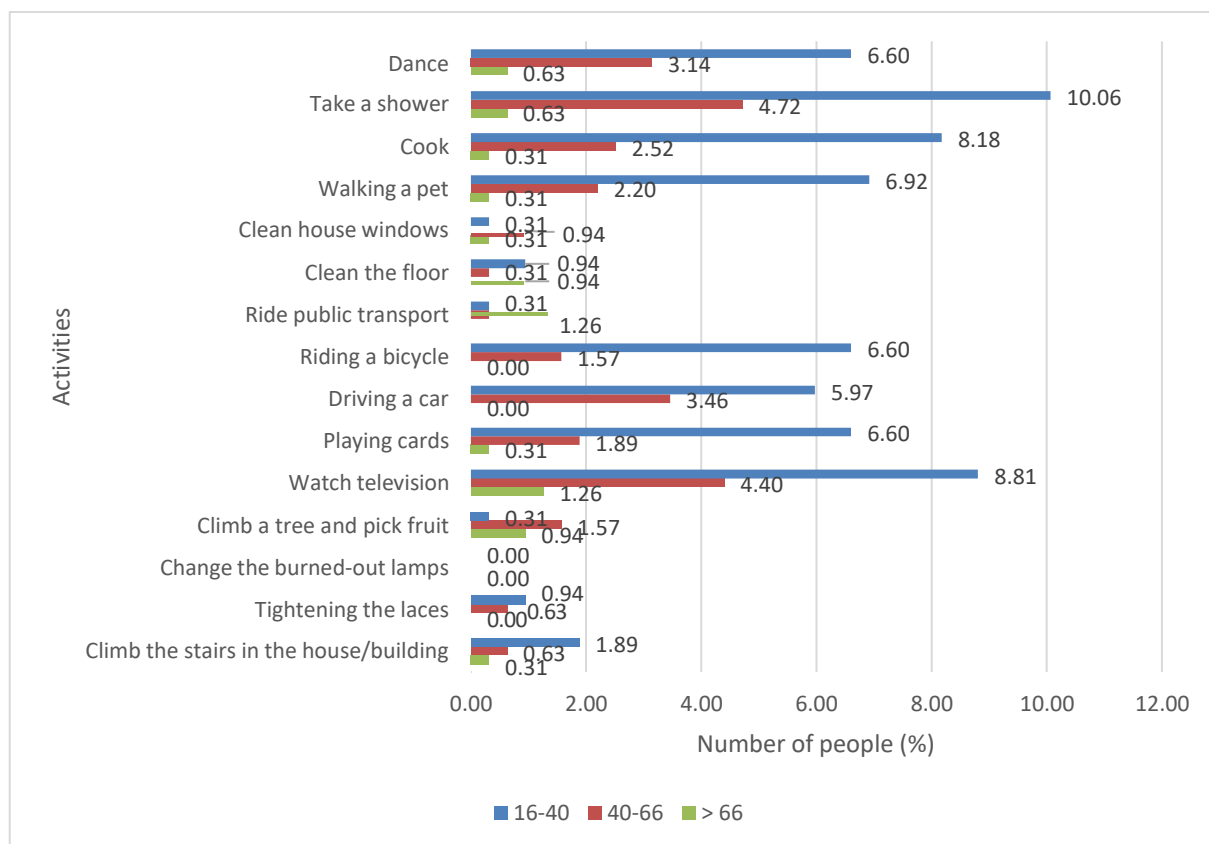


Figure 4.5 - Number of subjects by age (16-40, 40-66, > 66 years), in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.

According to Figure 4.4, the five most performed activities by people between 16 years and 40 years are taking a shower (11.99 %), climbing the stairs of the house/building (10.73 %), watching television (8.83 %), cooking (8.20 %), and driving a car (7.57 %). People between 40 years and 66 years old do most activities like watching television (4.73 %), climbing the stairs of the house/building (4.73 %), taking a shower (4.42 %), cooking (3.47 %), followed by cleaning the floor and driving a car, with the same percentage (3.15 %). Above 66 years of age, the most performed activities are taking a shower (1.58 %), cleaning the floor (1.26 %), watching television (1.26 %), cooking (0.95 %), and climbing the stairs of the house/building (0.63 %).

On the other hand, as Figure 4.5 shows, the five activities that people between 16 years and 40 years most enjoy doing are taking a shower (10.06 %), watching television (8.81 %), cooking (8.18 %), walking a pet (6.92 %), followed by dancing, riding a bicycle, and playing cards, all with the same percentage (6.60 %). Between 40 years and 66 years, the most cherished activities are taking a shower (4.72 %), watching television (4.40 %), driving a car (3.46 %), dancing (3.14 %), and cooking (2.52 %). Above the 66 years old, people enjoy riding public transport (1.26 %), watching television (1.26 %), cleaning the floor (0.94 %), climbing a tree and picking fruit (0.94 %), followed by dancing and playing cards with the same percentage (0.63 %).

4.4.3 Gender

From the participants, 65.62% was female. The Figures 4.6 and 4.7 present the answers of the subjects by gender about the ADLs they most perform, and the activities they most enjoy doing, in their daily lives, respectively.

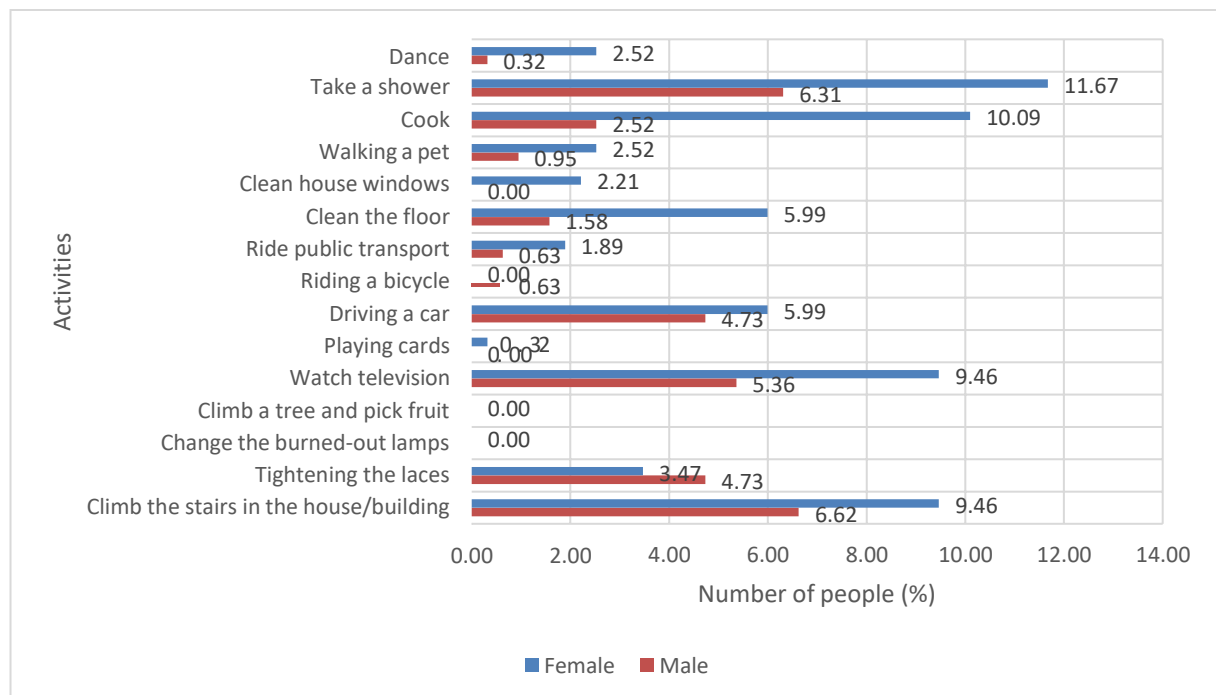


Figure 4.6 - Number of subjects by gender (female and male), in percentage, by activity, considering the five activities, out of fifteen, that people do the most.

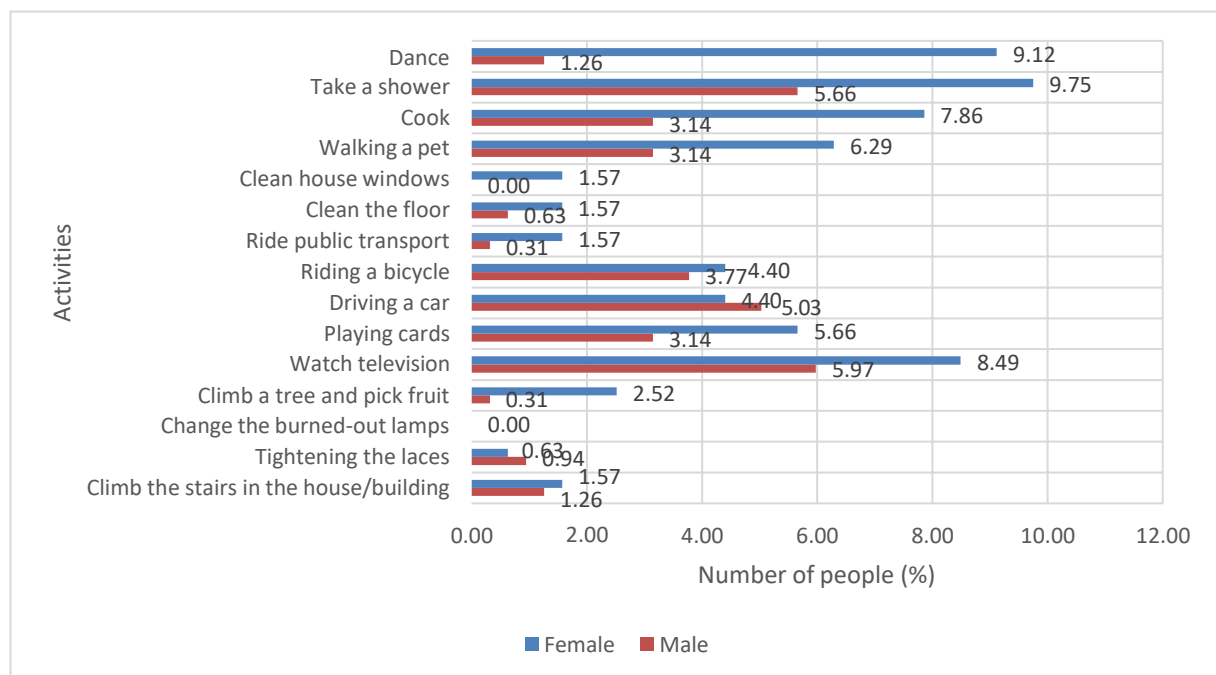


Figure 4.7 - Number of subjects by gender (female and male), in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.

Figure 4.6 shows that the five activities most performed by females are taking a shower (11.67 %), watching television, and climbing the stairs in the house/building with the same percentage (9.46 %), followed by cleaning the floor and driving the car, with the same percentage too (5.99 %). On the other

hand, the male gender reports performing more tasks such as climbing the stairs in the house/building (6.62 %), taking a shower (6.31 %), watching television (5.36 %), followed by driving a car and tightening the laces with the same percentage (4.73 %).

Regarding the five activities most appreciated by female gender, presented in Figure 4.7, these are taking a shower (9.75 %), dancing (9.12 %), watching television (8.49 %), cooking (7.86 %), and walking a pet (6.29 %). The male gender, on the other hand, prefers activities such as watching television (5.97 %), taking a shower (5.66 %), driving a car (5.03 %), riding a bicycle (3.77 %), followed by cooking, walking a pet, and playing cards with the same percentage (3.14 %).

4.4.4 Degree of daily physical activity

From the participants, 67.19 % consider themselves to be an active person. The Figures 4.8 and 4.9 present the results from the subjects by degree of daily physical activity about the five ADLs they most perform and most enjoy doing, respectively.

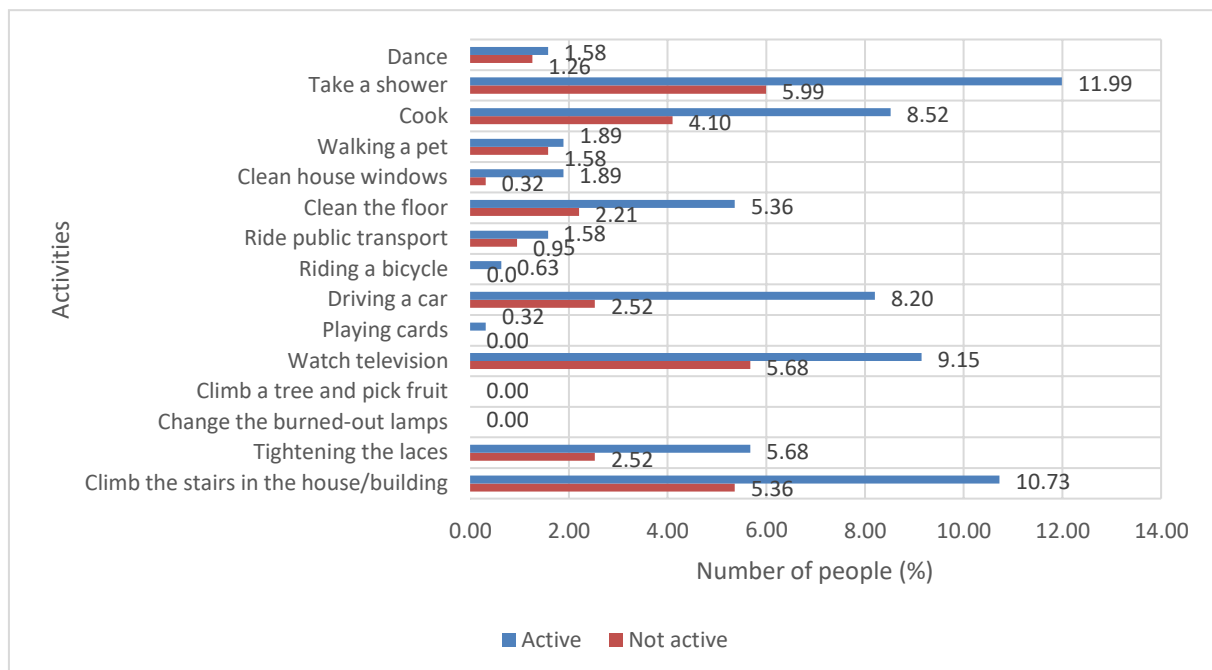


Figure 4.8 - Number of subjects by degree of daily physical activity (active and not active), in percentage, by activity, considering the five activities, out of fifteen, that people do the most.

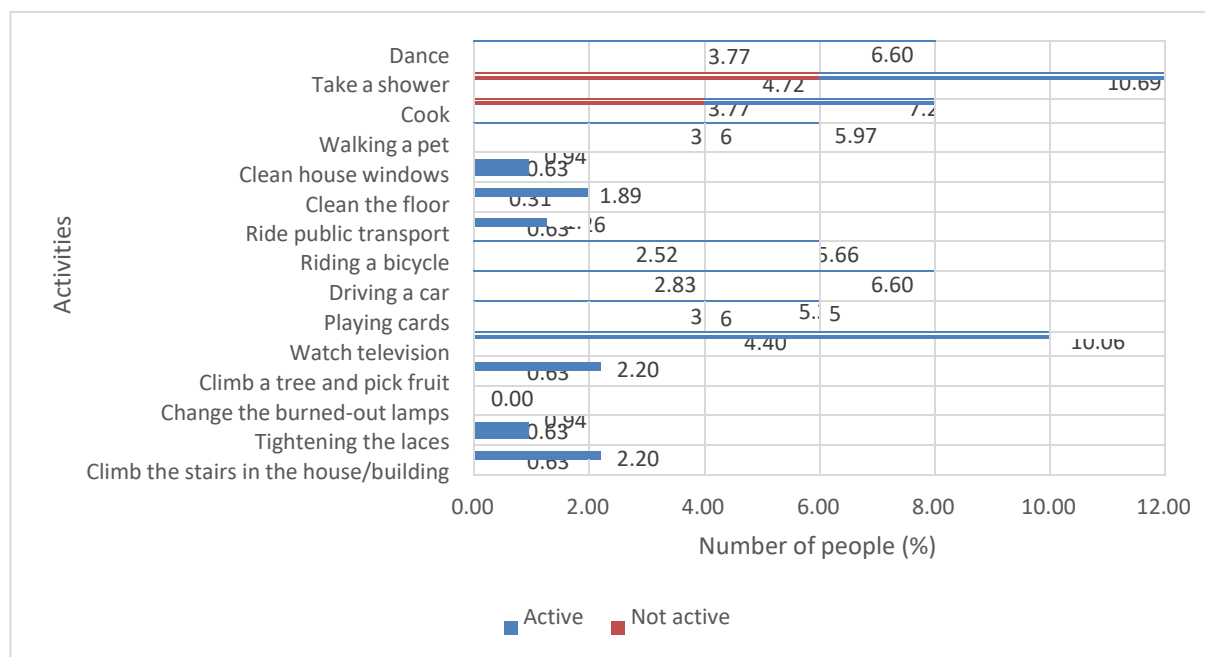


Figure 4.9 - Number of subjects by degree of daily physical activity (active and not active), in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.

Considering the Figure 4.8, it is possible to verify that the five activities most performed by physically active persons are taking a shower (11.99 %), climbing the stairs of the house/building (10.73 %), watching television (9.15 %), cooking (8.52 %), and driving a car (8.20 %). Regarding the not physically active people, the answers are taking a shower (5.99 %), watching television (5.68 %), climbing the stairs of the house/building (5.36 %), and cooking (4.10 %), followed by driving a car and tightening the laces with the same percentage (2.52 %).

On the other hand, when choosing the five ADLs they most like to do (Figure 4.9), physically active people chose taking a shower (10.69 %), watching television (10.06 %), and cooking (7.23 %), followed by dancing and driving a car on the same level (6.60 %). The not physically active people selected taking a shower (4.72 %), watching television (4.40 %), dancing and cooking with the same value (3.77 %), followed by walking a pet and playing cards with the same percentage (3.46 %).

4.4.5 Health condition

People were asked whether they had any illness that prevented them from being more active or not. In this way, and according to the answers, 90.62 % of population was healthy and the remaining 9.38 % was referred as injured subjects. Figures 4.10 and 4.11 represent the most performed and enjoyed activities in people's daily life, respectively, by health condition.

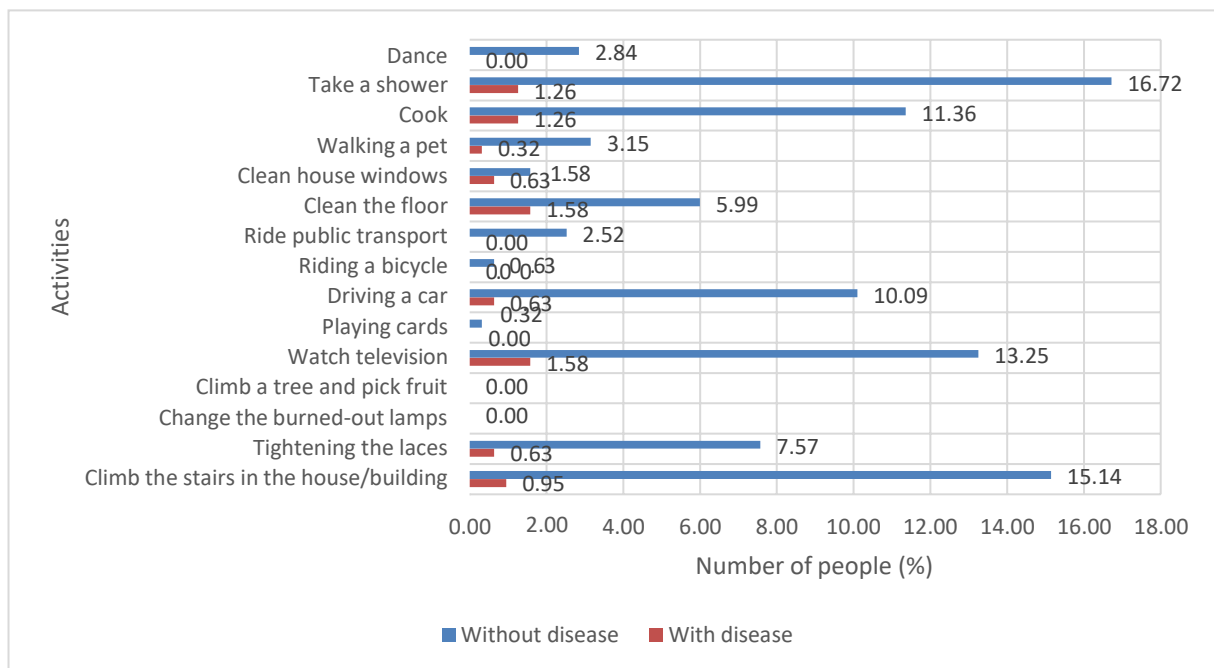


Figure 4.10 - Number of subjects with and without disease, in percentage, by activity, considering the five activities, out of fifteen, that people do the most.

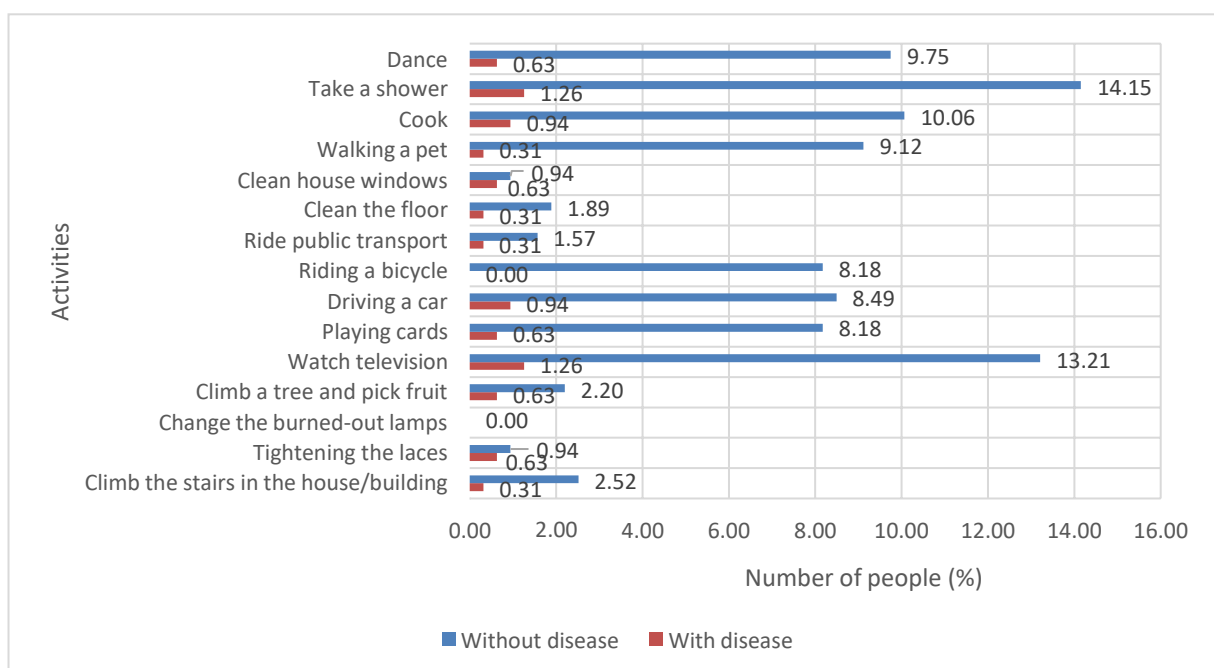


Figure 4.11 - Number of subjects with and without disease, in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.

Analysing the Figure 4.10, the five activities most performed by healthy people (without disease) are taking a shower (16.72 %), climbing the stairs of the house/building (15.14 %), watching television (13.25 %), cooking (11.36 %), and driving a car (10.09 %). On the other hand, people with a disease tend to do more activities such as cleaning the floor and watching television on the same level (1.58 %),

followed by taking shower and cooking (1.26 %), and finally climbing the stair of the house/building (0.95 %).

Figure 4.11 shows that the five activities most appreciated by the healthy population (without disease) are taking a shower (14.15 %), watching television (13.21 %), cooking (10.06 %), dancing (9.75 %), and walking a pet (9.12 %). People with illness, on the other hand, prefer activities such as taking a shower and watching television with the same percentage (1.26 %), cooking and driving a car at the same level too (0.94 %), followed by dancing, cleaning house windows, playing cards, and climbing a tree to pick fruit with the same percentage (0.63 %).

4.4.6 Degree of home urbanization

This subchapter aims to study if the urbanization of the place where the person lives influences the activities that they do the most and the ones they like to do the most. From the participants, 81.25 % live in the city. Figures 4.12 and 4.13 present the most performed and appreciated activities, respectively, by the subjects according to the degree of urbanization where they live (city or countryside).

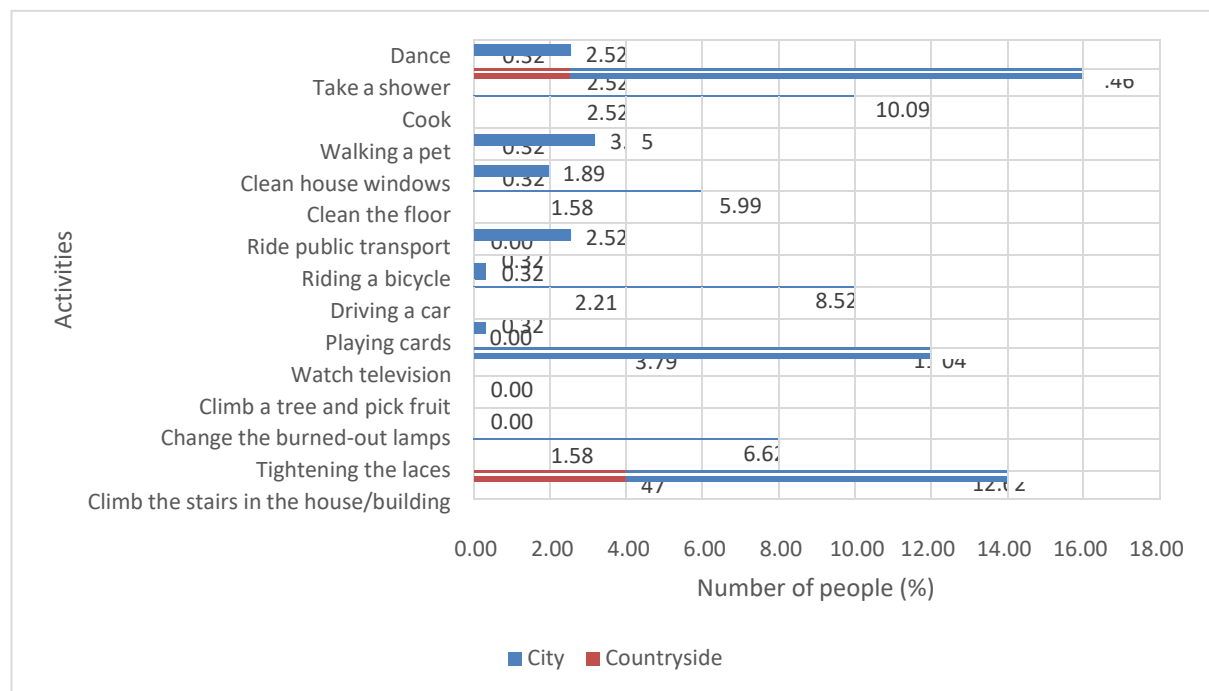


Figure 4.12 - Number of subjects living in the city and in countryside, in percentage, by activity, considering the five activities, out of fifteen, that people do the most.

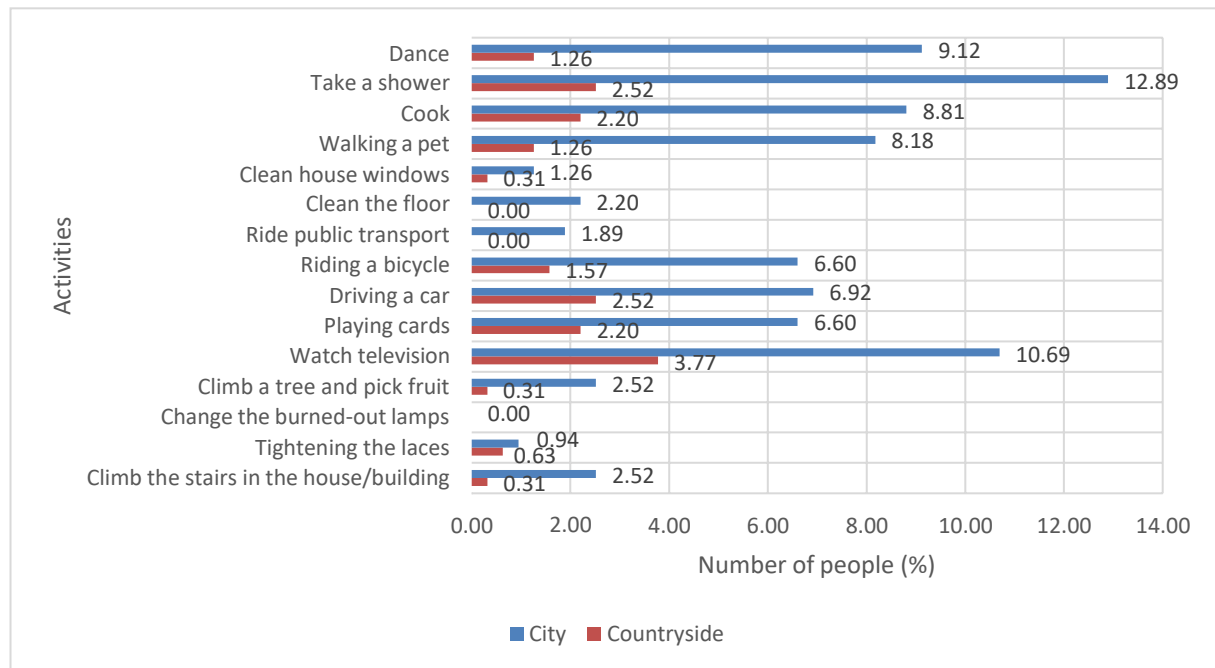


Figure 4.13 - Number of subjects living in the city and in countryside, in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.

Considering the Figure 4.12, the five most frequently performed activities by people living in the city are taking a shower (15.46 %), climbing the stairs in the house/building (12.62 %), watching television (11.04 %), cooking (10.09 %), and driving a car (8.52 %). People living in the countryside most often perform activities such as watching television (3.79 %), climbing the stairs in the house/building (3.47 %), taking a shower and cooking (2.52 %), followed by cleaning the floor and tightening the laces with the same percentage value (1.58 %).

Regarding the Figure 4.13, the five activities most enjoyed by people living in the city are taking a shower (12.89 %), watching television (10.69 %), dancing (9.12 %), cooking (8.81 %), and walking a pet (8.18 %). On the other hand, people living in the countryside, tend to enjoy more activities such as watching television (3.77 %), taking a shower and driving a car with the same percentage (2.52 %), cooking and playing cards also with the same percentage (2.20 %).

4.4.7 Type of transport daily used

The transport daily used by the population may influence the activities that people most perform and most like to perform in their daily lives. The number of individuals, in percentage, who commute by motorised or non-motorised transport is 63.75 % and 36.25 %, respectively. The answers of the subjects about the five activities they most perform and enjoy in their daily lives by type of transport daily used is presented in Figures 4.14 and 4.15, respectively.

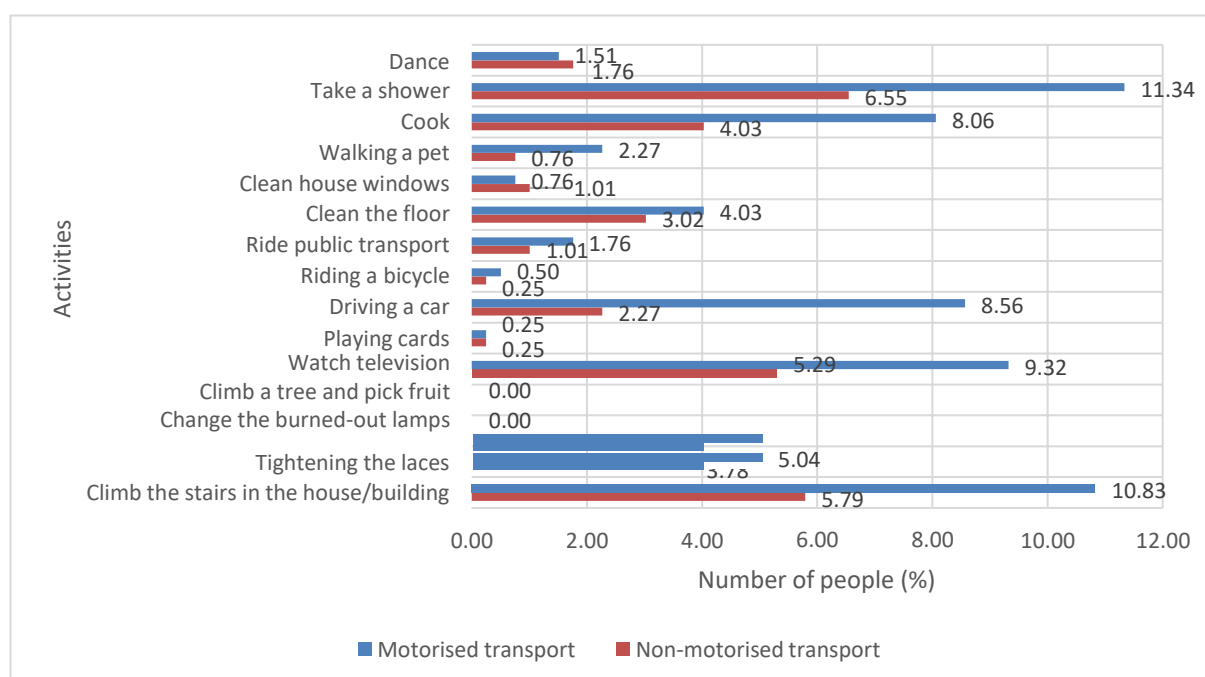


Figure 4.14 - Number of subjects who commute by motorised or non-motorised transport, in percentage, by activity, considering the five activities, out of fifteen, that people do the most.

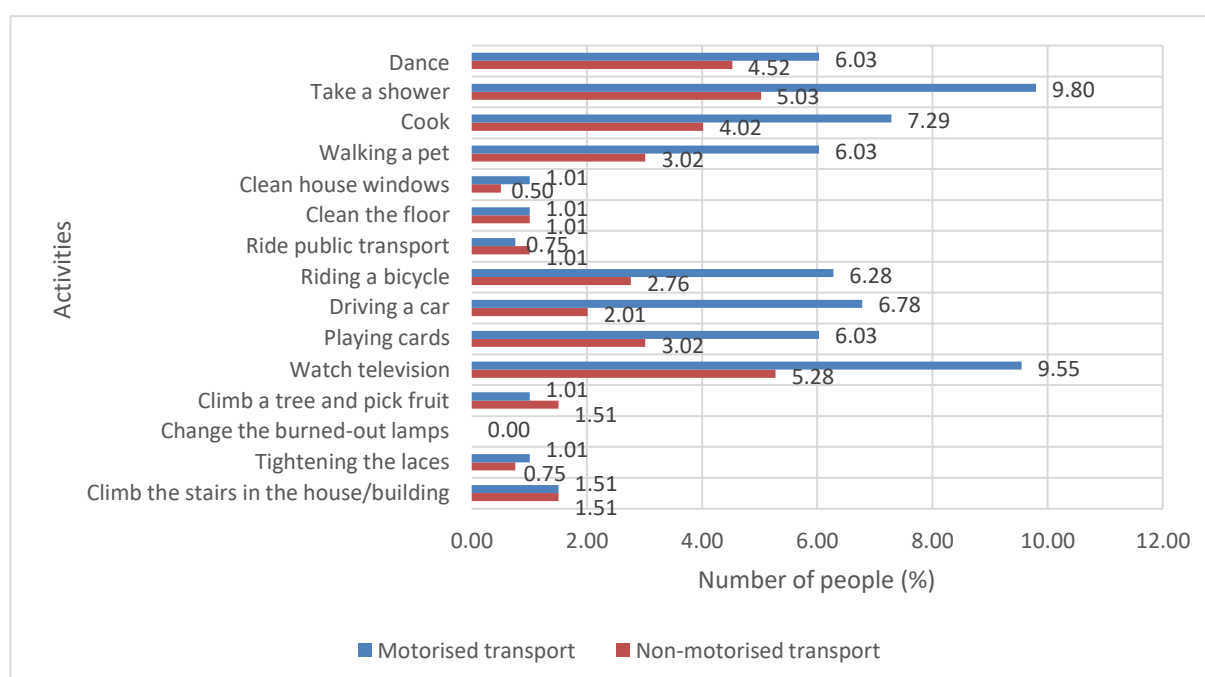


Figure 4.15 - Number of subjects who commute by motorised or non-motorised transport, in percentage, by activity, considering the five activities, out of fifteen, that people like to do the most.

Analysing the Figure 4.14, it is possible to verify that people who move more often through motorized transport (by car or public transport) do more activities such as taking a shower (11.34 %), climbing the stairs in the house/building (10.83 %), watching television (9.32 %), driving a car (8.56 %), and cooking (8.06 %). People who move more often through non-motorised transport (such as on foot)

tend to perform more frequently activities such as taking a shower (6.55 %), climbing the stairs of the house/building (5.79 %), watching television (5.29 %), cooking (4.03 %), and tightening the laces (3.78 %).

On the other hand, regarding the most appreciated activities (Figure 4.15), those who commute most often by motorised transport choose taking a shower (9.80 %), watching television (9.55 %), cooking (7.29 %), driving a car (6.78 %), and riding a bicycle (6.28 %). People who move more often by non-motorised transport tend to prefer activities such as watching television (5.28 %), taking a shower (5.03 %), dancing (4.52 %), and cooking (4.02 %), followed by walking a pet, and playing cards with the same percentage (3.02 %).

4.4.8 Conventional physical therapy

Figure 4.16 shows the number of participants who have never or ever had undertaken conventional physical therapy and, if so, whether they felt motivated or not during the sessions.

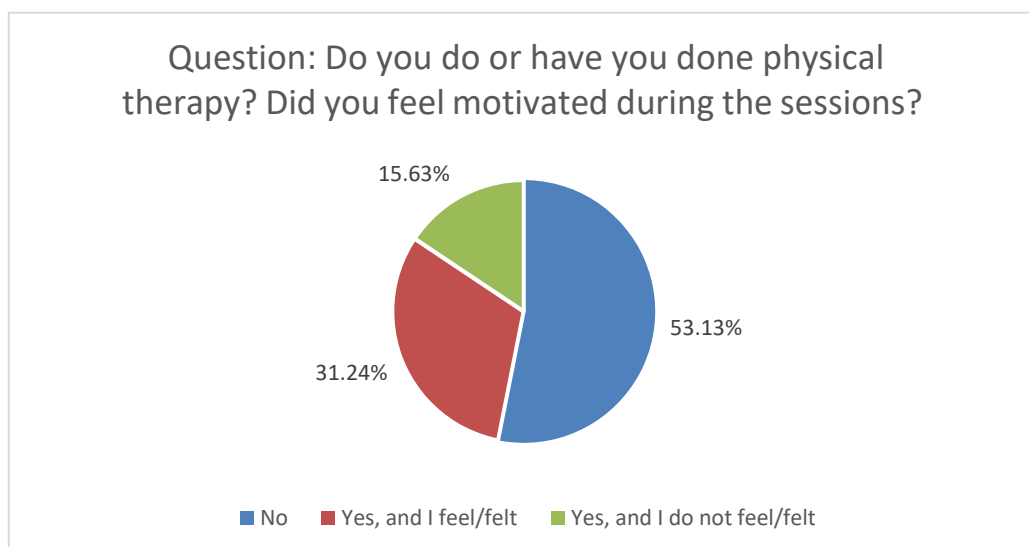


Figure 4.16 - Number of the individuals, in percentage, who do, did, or did not do physical therapy and whether they felt/feel or not motivated during sessions.

According to Figure 4.16, it is possible to verify that 53.13 % of participants never performed conventional physical therapy. Of the remaining subjects who have already done or are doing conventional physical therapy (46.87 %), 31.24 % felt or feel motivated during sessions. For those who do or have done conventional physical therapy and did not feel motivated (15.63 % of the participants), they were asked to indicate the reasons for such a statement. The answers of these subjects are presented in Figure 4.17.

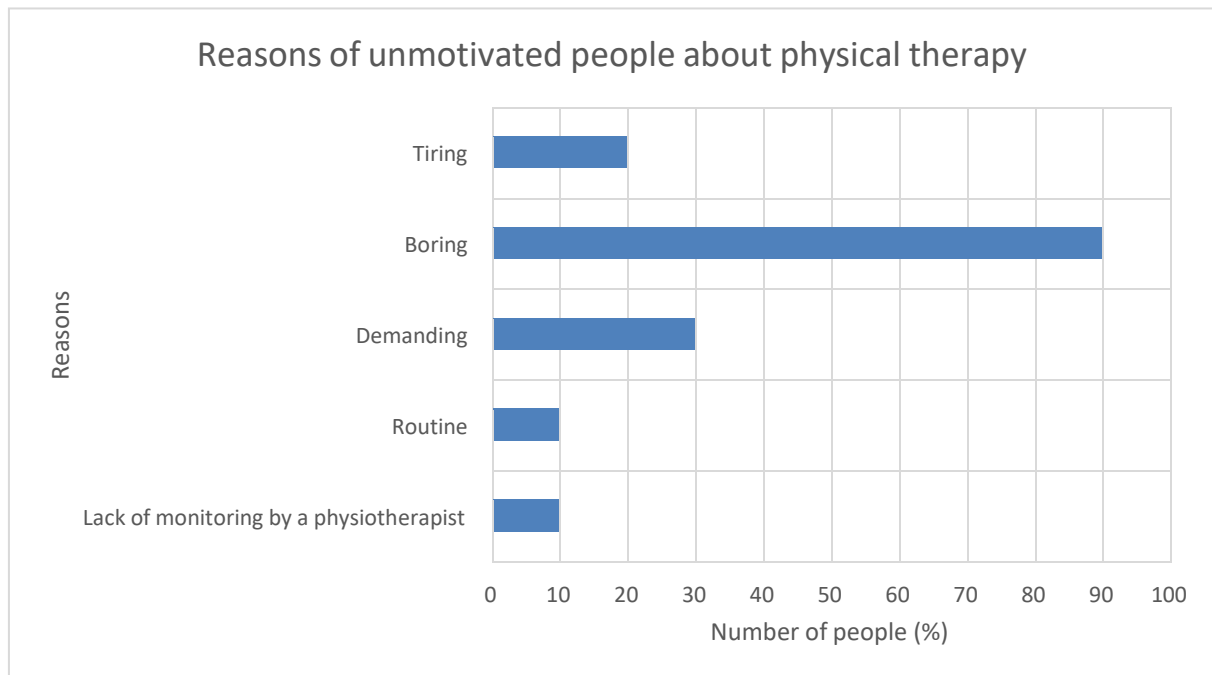


Figure 4.17 - Number of people, in percentage, among those who do not felt/feel motivated, by reasons (tiring, boring, demanding, other) for such discontentment about conventional physical therapy.

4.5 Discussion

This questionnaire intends to study what are the five ADLs, among fifteen options given, that people do the most and the ones they most enjoy doing to create a VR-based tool for balance training, as user-centered as possible. On the one hand, it is important to focus on the activities that the user does most in her/his daily life so that the training has a direct impact on her/his life. On the other hand, it is also relevant to focus the training on activities that the user enjoys doing so that rehabilitation motivates the users and does not become tedious and boring. In this manner, the user tends to actively participate in the training, accelerating the recovery process. Thus, it is important to find a middle ground between what the user does most and what the user likes to do the most to take advantage of both types of activities. This questionnaire is intended to check whether the tool created in this project is in line with a user-centered design and what can be done to improve it, guiding future research.

According to the global results from the questionnaire (Figures 4.1 and 4.2), there are four simultaneously most performed and liked activities: taking a shower, watching television, cooking, and driving a car. Climbing the stairs of the house/building is also one of the most performed activities; however, it is not in the subjects' preferences. This happens probably because it is an activity that people mostly perform for the need to access other places and does not contain any kind of pleasure. On the other hand, dancing and walking a pet are two of the most appreciated activities, although they are not

the most performed since most of the studied population has an active labour life. Overall, it is possible to verify that there is an agreement in four out of five activities, which indicates that the most performed activities are also among the most appreciated, and vice versa. Comparing the four activities that were simultaneously most performed and appreciated with the four virtual challenges created in this dissertation, it is possible to verify that there are three activities in common (taking a shower, watching television, and cooking), indicating that the developed VR tool follows the needs and the preferences of the participating population. Climbing stairs is the fourth motor task most performed by participants, which is included in the Fruit Cather virtual challenge.

Analysing the activities according to the subjects' age (Figures 4.4 and 4.5), despite the wide range of ages among the subjects, taking shower, climbing the stairs of the house/building, watching television, and cooking are four of the most frequently performed ADLs in common between the three age groups analysed. Driving a car is also one of the most performed activities in subjects belonging to the first two age groups (16-40 years and 40-66 years), and cleaning the floor is one of the most performed activities among the last two age groups (40-66 years and > 66 years). Thus, it is possible to determine that age has low influence on the tasks that people do more on a daily basis. However, since aging is more prone to diseases that limit balance, the age presents a decline in the functional status of patients being a common cause for limitations in ADLs [75]. Thus, it is normal that these people perform different ADLs than younger and healthier people. These results may be negatively influenced by the fact that the study population does not present balanced groups. Regarding the ADLs most appreciated by the subjects, the scenario changes. Watching television and dancing are the activities that satisfy the largest number of individuals regardless of age. Future research following a user-centered design should have in consideration that the age groups feel motivated with different ADLs.

Considering the gender factor, four of the five most performed activities are common to both genders (taking shower, climbing the stairs of the house/building, watching television, and driving a car, Figure 4.6). Regarding the most appreciated ADLs, among the choices made by both groups, there are also four activities in common (taking a shower, watching television, cooking, and walking a pet, Figure 4.7). These results suggest that gender has a low influence on the most performed and appreciated ADLs.

Diving the population into active and not active persons, both groups perform the most the same type of activities (taking a shower, climbing the stairs of the house/building, watching television, cooking, and driving a car, Figure 4.8). Regarding the five activities most appreciated by both groups, there are four in common (taking a shower, watching television, dancing, and cooking, Figure 4.9). Thus, the results

suggest that the degree of daily physical activity has a low influence on the most performed and appreciated ADLs.

Analysing the answers of the healthy people and of those who have an illness that prevents them from being more active, of the five activities most performed by both groups, four are common (taking a shower, climbing the stairs of the house/building, watching television, and cooking, Figure 4.10). Of the most appreciated activities, there are also four in common (taking a shower, watching television, cooking, and dancing, Figure 4.11). Although the results make it seem that the activities chosen not depend on the existence or not of an illness, the truth is that people who suffer a stroke, for example, lose much of their independence in ADL and suffer from a great deal of professional and social exclusion, given their limitations [49]. These results may be due to the fact that the number of people with an illness presented in the study is very low (9.38 %) compared to the health population (90.62 %) (Figure 4.12).

Between people living in a city and countryside, among the five activities most frequently performed, there are four in common (taking a shower, climbing the stairs of the house/building, watching television, and cooking, Figure 4.12). Of the activities most appreciated by both groups, there are three activities in common (taking a shower, watching television, and cooking, Figure 4.13). The results suggest that the degree of home urbanization has a low influence on the most performed and appreciated ADLs.

Finally, dividing the population into individuals who commute by motorised or non-motorised transport, of the five activities most performed, four are common to both groups (taking a shower, climbing the stairs of the house/building, watching television, and cooking Figure 4.14). Regarding the most enjoyed activities, there are three in common (taking a shower, watching television, and cooking, Figure 4.15). The results suggest that the type of transport daily used has a low influence on the most performed and appreciated ADLs.

In future research, to improve the accuracy of the conclusions, some factors should be considered such as: 1) balancing the data in all the studied factors; 2) the number of activities in the questionnaire should increase to allow diverged answers.

4.5.1 Conventional physical therapy

Most of the participants who answered this questionnaire do not perform or have never performed physical therapy (53.13 %). Of the remaining individuals, two-thirds (31.24 %) felt motivated during rehabilitation sessions. These people felt motivated because most probably they do not know any other type of rehabilitation, such as those including VR technologies. The remaining one-third (15,63 %) did not

feel motivated during the rehabilitation sessions. The reasons for such dissatisfaction variable among the participants, although most subjects mentioned that they were boring (90 %). These reasons prove what has already been mentioned during the literature review, indicating that many subjects do not feel motivated during conventional physical therapy. VR-based serious games may overcome the lack of motivation by encouraging the patients to perform motor tasks while immersed in an enthusiastic and interactable VRE.

4.6 Conclusions

Results from the questionnaire showed an agreement between the three most performed and liked activities, namely: taking a shower, watching television, and cooking. Most of the developed virtual challenges match these ADLs. The questionnaire's answer also demonstrates that the Fruit Catcher virtual challenge involves climbing the stairs, which is one of the most performed motor tasks. Overall, these findings suggest that the proposed VR tool was designed in accordance with the user's needs and preferences. The statistical analysis of the questionnaire highlights the need that serious games should be designed with a focus on the age of end-users. Moreover, it was possible to verify the need for highly motivating training tools to complement conventional therapies.

5. VALIDATION PROTOCOL

This chapter describes the protocol used in a preliminary validation of the VR-based tool for balance training with healthy subjects. This validation protocol followed a pre-post experimental study design aiming to evaluate the subjects' functional balance and mobility. First, the participants and their characteristics are specified, as well as the inclusion and exclusion criteria used to select them. Then, the VR intervention is explained, followed by the data collection carried out to achieve the intended validation. Finally, the data processing conducted to achieve the intended outcome measures is exposed, as well as the statistical analysis performed.

5.1 Participants

The validation protocol was conducted following the principles of the Declaration of Helsinki and the Oviedo Convention. The study was approved by the local ethical committee CEICVS 006/2020 at the University of Minho, and all the participants filled out an informed consent to participate in the current research.

Six healthy participants, all belonging to the experimental group (gender: 3 females and 3 males, age: 23.67 ± 0.94 years, height: 1.66 ± 0.09 m, body mass: 62.93 ± 10.65 kg) (Table 5.1), recruited and admitted in the University of Minho, were enrolled in the study according to the following inclusion criteria: age between 18-40 years, without any balance problems. The exclusion criteria were: heart and psychiatric (such as anxiety or post-traumatic stress) problems, have a pacemaker or another medical device implemented, be pregnant, feeling sick, fatigue or unwell in general, be under the influence of drugs/psychotropic substances, epileptic history or loss of knowledge moments, history of negative physical or psychological reactions to certain real-life circumstances, history of loss of consciousness, convulsions, involuntary movements, dizziness, disorientation, nausea, vertigo, and drowsiness, have eye pain or discomfort, eyestrain, tics or eye disorders (such as double altered, or blurred vision), have coordination failures or other seasickness-like symptoms.

Table 5.1 – Gender, age (years), height (m), and body mass (kg) of each participant

Participant	Gender	Age (years)	Height (m)	Body mass (kg)
Participant 1	Female	25	1.53	46.2
Participant 2	Male	23	1.75	65.7
Participant 3	Female	23	1.58	56.6
Participant 4	Male	23	1.77	74.5
Participant 5	Female	23	1.61	57.8
Participant 6	Male	25	1.70	76.8

5.2 Intervention

Before the VR intervention, the participants were instrumented with an HTC Vive Pro and the full-body configuration of the MVN Awinda. Then, the HMD and sensor system were calibrated according to the systems' guidelines. The experimental study protocol consisted of the following subsequent trials: 1 data acquisition trial to assess pre-study balance performance (BBS and TUG), 1 VR familiarization trial, 1 VR training session with 2 trials (T1 and T2 for first and second trials, respectively), and 1 post-study data acquisition trial to assess balance performance (BBS and TUG). The VR familiarization trial and the VR training session were conducted in a row for each serious game. The VR training included the four virtual challenges: Fruit Catcher, Cooking, Take a Shower, and Watch Tv, with a maximum duration of 3 minutes each, and 3 minutes of rest between virtual challenges or trials (VR training lasted, approximately, 1h). The order of the virtual challenges was randomly chosen to avoid carry-out time effect. The participants self-selected the order to pick up the apples and the ingredients in the virtual challenges Fruit Catcher and Cooking, respectively.

During all the VR sessions, once the participant was isolated from the real world, there was always one person accompanying her/him to provide guidance through verbal instructions and prevent falls. Figure 5.1 shows pictures of the participant 6 during the VR training, performing the four virtual challenges. The monitor displays what the participant is seeing on the HMD.

In data acquisition trials, the BBS and TUG clinical tests were performed once they are the most used clinical outcomes in literature (as appointed in subchapter 2.2.5) to assess the subject's ability to safely perform tasks while maintaining balance (static and dynamic balance), and to assess mobility and walking ability (functional mobility), respectively.



A)



B)



C)



D)

Figure 5.1 - Participant 6 during VR training. (A) While catching apples in “Fruit Catcher” virtual challenge. (B) While walking in “Watch TV” virtual challenges. (C) While collecting food from the kitchen shelves in “Cooking” virtual challenge. (D) While entering in the bathtub in “Take a Shower” virtual challenge.

5.3 Data Collection

From the total of 6 participants, all of them completed the entire protocol. During the intervention, sensor-based and clinical assessments were performed for each participant, by the same operator, in order to reduce potential errors that may arise from different ways of performing the same data extraction. The sensor-based assessment was carried out using the MTw' sensors of the IMU-based motion capture system Xsens MVN Awinda, in a full-body configuration, at a frequency of 60 Hz. Note that no data were acquired during the familiarization procedure.

In general, the primary outcomes during the VR intervention (Table 5.2) were the COM's position and velocity in the anteroposterior (AP) and mediolateral (ML) directions. The secondary outcomes (Table 5.2) were divided into: 1) sensor-based outcomes estimated by MVN Analyze such as knee joint angle on the sagittal plane, hand position to the left, right and forward directions, and foot contact data; 2) virtual challenges' scores measured through Unity, namely, number of steps climbed, number of apples caught, number of times the user kicked the bathtub rim, sound playing duration inside the bathtub, number of ingredients caught in kitchen's shelves, and television state achieved. The maximum scores of the virtual challenges are 6 steps climbed, 9 apples caught, no kicks on the bathtub rim, sound playing during 10 s inside bathtub, 6 ingredients caught on kitchen' shelves, and television on state achieved.

During data acquisition trials, the scores of BBS and the TUG tests were collected. Further, sensor-based measures were collected (one acquisition for all the TUG's activities and one acquisition per each BBS' task), using the Xsens MVN Awinda, to study the functional balance and mobility of the participants objectively during the tasks addressed by these clinical tests. The COM's position and velocity on the AP and ML directions are the primary outcomes (Table 5.3). The secondary outcomes (Table 5.3) of BBS were: 1) knee joint angle on the sagittal plane for the sitting to standing, standing to sitting, place alternate foot on step while standing unsupported, and standing on one leg tasks; 2) and hand position for the reaching forward task. For walking phase of TUG test, the secondary outcomes (Table 5.3) were knee joint angle on the sagittal plane and foot contact.

Finally, two user's experience evaluation tests (secondary outcomes), the Igroup Presence Questionnaire (IPQ) and the Intrinsic Motivation Inventory (IMI), were answered after the VR intervention. The IPQ, aiming to assess the user's sense of presence in VREs, is a questionnaire with 14 questions (with answers on a scale of 1 to 7). It assesses the following presence dimensions: presence as transportation (Spatial Presence), presence as immersion (Involvement) and presence as realism (Experienced Realism), with maximum scores of 6.33, 6.00, and 7.00, respectively. Finally, there is a fourth metric (Global Presence) resulting from the average of the three factors mentioned above [76],

with a maximum score of 6.44. For the IMI, intended to assess the participants' subjective experience related to the VR experience lived by them during the VR training [77], the subscales to be analysed were chosen according to the ones that best fit with the activity performed: Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, and Value/Usefulness. The questionnaire had a total of 30 questions, of which 27 were rated on a scale of 1 to 7, with the remaining 3 questions being open-ended. Thus, each of the subscales presents the best score for 7.00, 7.00, 2.20, 1.00, and 7.00, respectively. For the third and fourth subscales, the lower and closer to the minimum value (2.20 and 1.00, respectively) the better, contrary to the remaining subscales that the higher the score the better.

Table 5.2 – Virtual challenges and their respective outcome measures

Virtual Challenge	Motor Tasks	Sensor-based Outcomes		Virtual Challenges Scores
Fruit Catcher	- Stepping - Weigh shifting - Looking over the shoulders - Reaching	Primary	During climbing stairs: - COM's position on the AP and ML directions - COM's velocity on the AP and ML directions During catching fruits: - COM's position on the AP and ML directions - COM's velocity on the AP and ML directions	- Number of steps climbed - Number of apples caught
		Secondary	- Knee joint angle on the sagittal plane - Hand position to the left, right, and forward directions	
Take a Shower	- Knee flexion/extension - Stand upright on one leg	Primary	While entering in the bathtub: - COM's position on the AP and ML directions - COM's velocity on the AP and ML directions Inside the bathtub: - COM's position on the AP and ML directions - COM's velocity on the AP and ML directions	- Number of times the user kicked the bathtub rim - Sound playing duration inside bathtub
		Secondary	Knee joint angle on the sagittal plane	
Cooking	- Knee flexion/extension - Weigh shifting - Trunk and pelvic/hip movement	Primary	- COM's position on the AP and ML directions - COM's velocity on the AP and ML directions	- Number of ingredients caught in kitchen's shelves
Watch Tv	- Stand-to-sit - Sit-to-stand - Walking	Primary	Sit-to-stand: - COM's position on the AP and ML directions - COM's velocity on the AP and ML directions Stand-to-sit: - COM's position on the AP and ML directions - COM's velocity on the AP and ML directions During walking: - COM's position on the AP and ML directions - COM's velocity on the AP and ML directions	- Television state achieved
		Secondary	- Knee joint angle on the sagittal plane - Foot contact	

Table 5.3 – Clinical scales and their respective outcome measures

Clinical Scale	Motor Tasks	Sensor-based Outcomes		Clinical Scales Scores
BBS	1. Standing unsupported 2. Sitting with back unsupported 3. Transfers 4. Standing unsupported with eyes closed 5. Standing unsupported with feet together 6. Pick up an object from the floor 7. Turn to look behind the shoulders 8. Turn 360 degrees 9. Standing unsupported one foot in front	Primary	- COM's position on the AP and ML directions - COM's velocity on the AP and ML directions	- Score for each BBS' task
	10. Sitting to standing 11. Standing to sitting 12. Place alternate foot on step while standing unsupported 13. Standing on one leg	Primary	- COM's position on the AP and ML directions - COM's velocity on the AP and ML directions	
		Secondary	Knee joint angle on the sagittal plane	
	14. Reaching forward with outstretched arms while standing	Primary	- COM's position on the AP and ML directions - COM's velocity on the AP and ML directions	
		Secondary	Hand position to the left, right, and forward directions	
TUG	1. Sit-to-stand 2. Walking 3. Stand-to-sit	Primary	- COM's position on the AP and ML directions - COM's velocity on the AP and ML directions	- Time to perform the TUG
		Secondary	- Knee joint angle on the sagittal plane - Foot contact	

5.4 Data processing

The data processing was carried out using Matlab software (MATLAB R2020a, © 1994-2021 The MathWorks, Inc.). Firstly, data from the virtual challenges of Fruit Catcher, Take a Shower, and Watch Tv, and from the TUG test were segmented between the related motor tasks. For the Fruit Catcher and Take a Shower virtual challenges, there are two distinct activities to be analysed: climbing the stairs and catching fruits; and entering in the bathtub and standing on one leg while inside the bathtub, respectively. For the Watch Tv virtual challenge and the TUG clinical test, there are three different activities: sit-to-stand, walking, and stand-to-sit. The segmentation performed was done by visual inspection of the kinematic data or by foot contact. Data from the Cooking virtual challenge and the BBS' tasks were not segmented.

Secondly, metrics were calculated from the sensor-based data. The COM displacement in the AP and ML directions was calculated by the difference between the highest and the lowest values of the COM's position in the x and y axes, respectively. The maximum and minimum COM velocity in the AP and ML directions correspond to the highest and lowest values of the COM velocity in the x and y axes, respectively. The ROM of the left and right knee joint angle in the sagittal plane was determined by the difference between the highest and the lowest angle in the z-axis of the left and right knee joint, respectively. The maximum left- and right-hand position corresponds to the maximum left- and right-hand position on the y-axis, respectively. On the other hand, the maximum forward hand position corresponds to the highest value on the x-axis between the maximum positions of the left and right hands. Regarding spatiotemporal gait metrics (stride length and stride time, respectively), both were determined based on the right leg (participants' dominant leg) foot contact. The stride length was determined by the difference of the right foot position, on the x-axis, between consecutive right foot contacts on the ground. Additionally, the stride time was calculated through the difference of the frames between consecutive right foot contacts on the ground and, then, divided by the sampling frequency (60 Hz). The metrics related to the walking motor task were normalized per gait cycle, making the subsequent calculation of mean and standard deviation (SD) for data presentation.

5.5 Statistical Analysis

The statistical analysis was performed through IBM SPSS software version 26.0 (for Windows) (IMP Corp, Armonk, NY, USA). The data normality and homoscedasticity were assessed using Kolmogorov-Smirnov's and Levene's tests, respectively. Two-tailed *t*-tests were performed for the parametric metrics

considering the “time” factor. The Wilcoxon signed-rank test was applied to variables where at least one of the assumptions (normality or homoscedasticity) was not verified. All statistical tests were executed considering a confidence level of 95 % ($\alpha = 0.05$) and paired samples. Only the primary outcomes were statistically analysed.

The statistical tests were conducted to evaluate the following null hypotheses: 1) there are no statistically significant differences between trial 1 and trial 2 of VR intervention; 2) there are no statistically significant differences between before and after VR intervention.

5.6 Conclusions

The six participants have successfully and safely completed the intervention, within 1h, which consisted of 1 VR training session with 1 VR familiarization trial and 2 data acquisition data trials in a row, per virtual challenge.

The primary outcomes during VR intervention and the BBS and TUG clinical tests are the COM's position and velocity in the AP and ML directions. Secondary outcomes included: 1) knee joint angle on the sagittal plane, hand position to the left, right and forward directions, and foot contact data, for both; 2) virtual challenges, during VR intervention; 3) clinical scales scores, for BBS and TUG. Both primary and secondary outcomes were well-collected during the intervention. Finally, all participants answered the IMI and IPQ user's experience evaluation tests after the VR intervention (secondary outcome).

Data processing functions were successfully implemented to determine the metrics of COM displacement, minimum and maximum COM velocity on the AP and ML directions, ROM of the knee joint angle on the sagittal plane, maximum hand position to the left, right, and forward directions, and spatiotemporal gait parameters (stride length and stride time, respectively). Further, the statistical analysis, including the two-tailed *t*-tests for parametric metrics and Wilcoxon signed-rank tests for non-parametric metrics, was carried out with success for the estimated metrics.

6. RESULTS AND DISCUSSION

This chapter aims to present the results from the preliminary validation of the VR-based tool for balance training. The results are divided into three parts. First, all primary and secondary outcomes concerning the VR intervention are presented. The second part of this chapter presents the results of the sensor-based and clinical scales assessment performed before and after the VR intervention for the BBS and TUG related motor activities. Third, the answers of the user's experience evaluation tests are shown.

6.1 During VR Intervention

After processing the data, the tables with all the primary and secondary outcomes presented in Appendix I were obtained, as well as the figures presented in this subchapter, illustrating the COM displacement in the AP direction by the ML direction per each virtual challenge.

6.1.1 Fruit Catcher

Figure 6.1 presents the COM displacement in the AP direction by the ML direction for all participants in each trial during the tasks of climbing stairs and catching fruits of the virtual challenge Fruit Catcher.

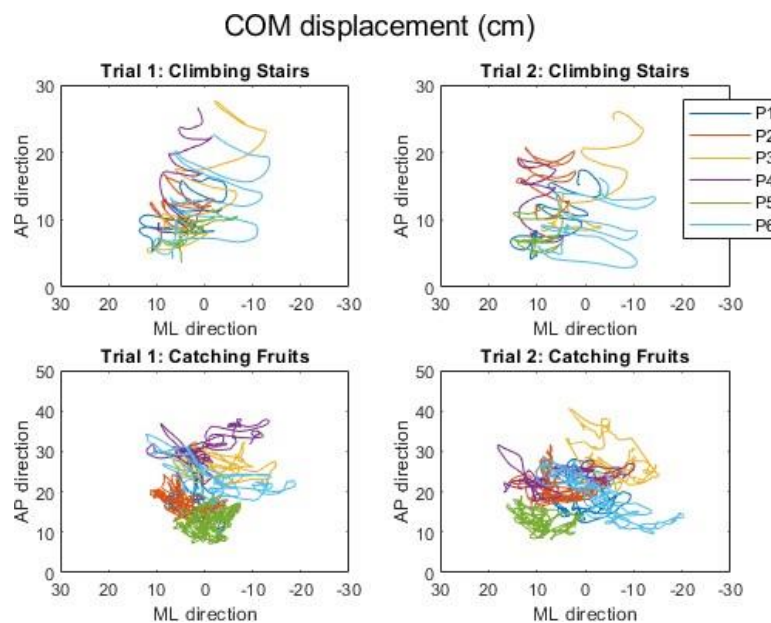


Figure 6.1 - COM displacement (cm) in the AP direction by the ML direction, for all participants in each trial during the tasks of climbing stairs and catching fruits, of the virtual challenge "Fruit Catcher".

After the construction of the Tables 0.1 and 0.2 presented in Appendix I, the data was statistically evaluated, comparing the primary outcomes from T1 versus T2 for each virtual challenge. Table 6.1 presents the results of parametric (paired samples t-test) and non-parametric metrics (Wilcoxon signed-rank test) for the virtual challenge Fruit Catcher.

Table 6.1 - Mean and SD of T1 and T2, and p-value of the paired samples test and Wilcoxon test for COM displacement (Disp) and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for climbing stairs and catching fruits motor tasks of the virtual challenge "Fruit Catcher", considering the time condition and a significance level of 5 %. The most representative results (*p*-value < 0.05) appear in bold

Fruit Catcher			Paired Samples Test		Test Statistics ^a	
	Mean ± SD		#test		Wilcoxon	
	T1	T2	<i>t</i>	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Climbing Stairs						
DispAP_CS	14.485 ± 2.531	12.437 ± 1.459	-	-	-1.153 ^b	.249
DispML_CS	17.868 ± 2.256	15.982 ± 2.507	2.069	.093	-	-
VelMinAP_CS	- 5.593 ± 0.376	- 4.863 ± 0.321	-1.646	.161	-	-
VelMaxAP_CS	10.640 ± 1.392	10.063 ± 0.760	.483	.649	-	-
VelMinML_CS	-20.152 ± 2.847	-20.047 ± 2.413	-0.100	.924	-	-
VelMaxML_CS	18.337 ± 1.649	16.882 ± 1.345	1.245	.268	-	-
Catching Fruits						
DispAP_CF	15.013 ± 1.701	16.015 ± 1.403	-.461	.664	-	-
DispML_CF	20.332 ± 2.948	22.113 ± 2.430	-1.379	.226	-	-
VelMinAP_CF	-11.300 ± 0.652	-12.015 ± 1.148	.851	.434	-	-
VelMaxAP_CF	9.482 ± 0.687	9.358 ± 0.943	.173	.869	-	-
VelMinML_CF	-14.210 ± 2.436	-13.285 ± 1.723	-.344	.745	-	-
VelMaxML_CF	14.323 ± 2.485	11.408 ± 1.574	1.530	.187	-	-
a. Wilcoxon Signed Ranks Test						
b. Based on positive ranks						

Table 6.2 indicates the mean and SD of the secondary outcomes of all the participants, for each trial of the virtual challenge Fruit Catcher, namely the ROM of left and right knee joint angles on the sagittal plane (degrees) during climbing stairs, and the maximum hand position to the left, right, and forward directions (cm) during catching fruits.

Table 6.2 – Mean and SD of the ROM of the left and right knee joint angles on the sagittal plane (degrees), and the maximum hand position to the left, right, and forward directions (cm) in each trial of the virtual challenge “Fruit Catcher”

Secondary Outcomes	Mean $\pm$ SD	
	T1	T2
Climbing stairs		
ROM of the knee joint angles (degrees)		
Left knee	79.18 $\pm$ 7.49	79.18 $\pm$ 9.28
Right knee	77.38 $\pm$ 7.25	74.63 $\pm$ 6.81
Catching Fruits		
Maximum hand position (cm)		
Left	51.67 $\pm$ 6.21	51.38 $\pm$ 7.62
Right	69.87 $\pm$ 8.17	69.25 $\pm$ 7.44
Forward	86.18 $\pm$ 4.29	86.80 $\pm$ 6.47

Table 6.3 shows the virtual challenge scores for each trial of both the motor tasks, climbing stairs and catching fruits, of the virtual challenge Fruit Catcher.

Table 6.3 – Number of steps climbed, and number of apples caught in each trial of climbing stairs and catching fruits, respectively, in virtual challenge “Fruit Catcher”

Virtual challenge scores				
Participants	Number of steps climbed		Number of apples caught	
	T1	T2	T1	T2
P1	6	6	6	6
P2	6	6	5	7
P3	6	6	7	6
P4	6	6	9	9
P5	6	6	4	4
P6	6	6	9	9

Although the statistical analysis performed to the virtual challenge Fruit Catcher did not indicate any significant difference between trials (p -value > 0.05), the data of COM displacement in the ML direction presents a positive probably value ($t = 2.069$) (Table 6.1). This indicates a general trend of its decreasing between trials. Since people continued to perform the intended activity exquisitely as they were able to climb all 6 stairs, a decrease in the COM value indicates that, in general, participants in the second trial were able to achieve the same goal by varying the COM less, which means increased stability of balance. As this motor activity involves a greater variation of COM in the ML direction than on the AP axis, an improvement in COM displacement in this direction (ML) is a very positive assessment. Although the lower variation of COM displacement in the AP direction, participants also decreased this metric (14.485 ± 2.531 cm on T1, and 12.437 ± 1.459 cm on T2) (Table 6.1). Considering this, it is possible to verify that despite the improvements at the balance level, there was no increase in COM velocity in any direction of any of the axes (mean and standard deviation in T1 is lower than in T2) (Table 6.1).

Regarding the second motor task of catching fruits, there was only an increase in AP velocity in the negative direction of the axis (after picking a fruit, the user returned to the initial resting position) (Table 6.1). The no decrease in COM displacement in either direction (AP and ML) can be explained by the fact that participants in the second trial were trying to pick more fruit than in the first trial. This behaviour is shown by increasing the maximum hand position in forward direction (Table 6.2). Furthermore, with exception of P4 and P6, none of the other participants succeeded in picking the maximum number of apples, in both trials (Table 6.3), which triggers an interest in reaching further and picking more fruit. P2 was able to increase from 5 to 7 apples picked between T1 and T2 (Table 6.3). All of this can justify the non-decrease of COM displacement.

6.1.2 Take a Shower

Figure 6.2 illustrates the participants' COM displacement for AP direction by ML direction in each trial during the tasks of entering in the bathtub and standing on one leg inside the bathtub of the virtual challenge Take a Shower.

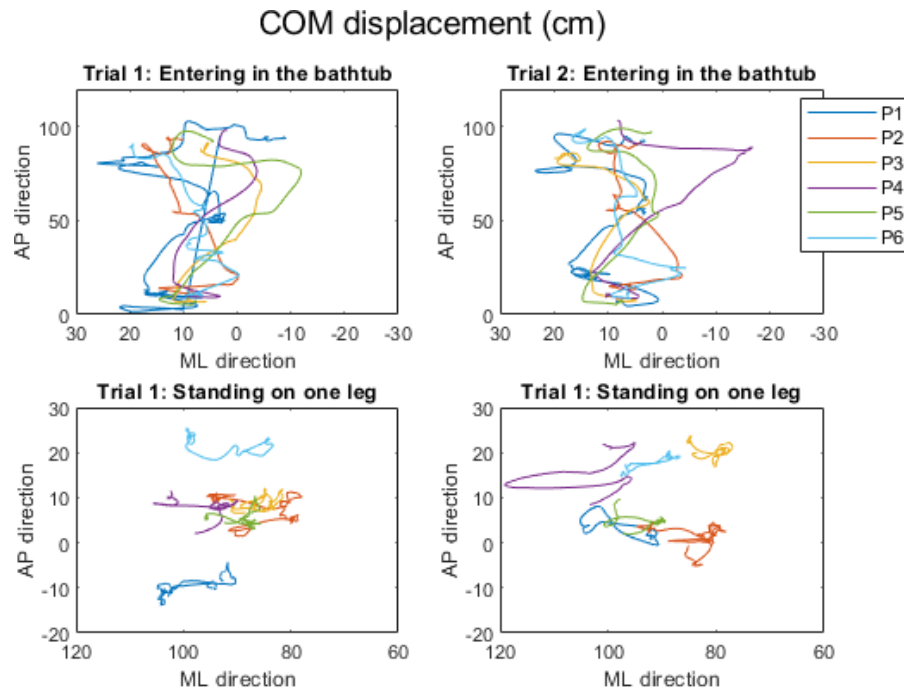


Figure 6.2 - COM displacement (cm) in the AP direction by the ML direction for all participants in each trial during the tasks of entering in the bathtub and standing on one leg inside the bathtub, of virtual challenge "Take a Shower".

After the construction of the Tables 0.3 and 0.4 presented in Appendix I, the data was statistically evaluated, comparing the primary outcomes from T1 versus T2 for each virtual challenge. Table 6.4 presents the results of parametric (paired samples *t*-test) and non-parametric metric (Wilcoxon signed-rank test) for the virtual challenge Take a Shower.

Table 6.4 - Mean and SD of T1 and T2, and the p-value of the paired samples test and Wilcoxon test for COM displacement (Disp) and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for entering in the bathtub and standing on one leg inside the bathtub inside the bathtub motor tasks of the virtual challenge “Take a Shower”, considering the time condition and a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Take a Shower	Paired Samples		Test Statistics ^a			
	Mean $\pm$ SD		Test		Wilcoxon	
	T1	T2	#test			
			<i>t</i>	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Entering in the bathtub						
DispAP_EB	88.885 $\pm$ 2.972	88.095 $\pm$ 2.910	.267	.800	-	-
DispML_EB	22.047 $\pm$ 3.055	20.137 $\pm$ 2.313	.476	.654	-	-
VelMinAP_EB	-12.997 $\pm$ 2.679	-11.733 $\pm$ 1.569	-.535	.615	-	-
VelMaxAP_EB	55.027 $\pm$ 6.794	60.055 $\pm$ 4.992	-1.029	.351	-	-
VelMinML_EB	-22.632 $\pm$ 4.469	-20.440 $\pm$ 2.854	-.475	.655	-	-
VelMaxML_EB	21.607 $\pm$ 4.021	22.497 $\pm$ 2.893	-.216	.837	-	-
Standing on one leg						
DispAP_IB	8.213 $\pm$ 0.683	8.765 $\pm$ 1.188	-.607	.570	-	-
DispML_IB	14.152 $\pm$ 1.289	14.305 $\pm$ 2.264	-.084	.936	-	-
VelMinAP_IB	-9.010 $\pm$ 1.298	-6.780 $\pm$ 0.753	-1.128	.310	-	-
VelMaxAP_IB	9.163 $\pm$ 0.827	8.407 $\pm$ 0.826	.576	.590	-	-
VelMinML_IB	-10.833 $\pm$ 1.553	-13.295 $\pm$ 4.339	-	-	-.105 ^c	.917
VelMaxML_IB	16.878 $\pm$ 1.839	18.520 $\pm$ 4.925	-.404	.703	-	-
a. Wilcoxon Signed Ranks Test						
c. Based on negative ranks						

Table 6.5 presents the mean and SD of the ROM of left and right knee joint angles on the sagittal plane (degrees) during entering in the bathtub and standing on one leg inside the bathtub (secondary outcomes), of all the participants, for each trial of the virtual challenge Take a Shower.

Table 6.5 - Mean and SD of the ROM of the left and right knee joint angles on the sagittal plane (degrees) in each trial of the virtual challenge "Take a Shower"

Secondary Outcomes	Mean $\pm$ SD	
	T1	T2
Entering in the bathtub		
ROM of the knee joint angles (degrees)		
Left knee	109.04 $\pm$ 2.41	108.32 $\pm$ 5.41
Right knee	107.46 $\pm$ 7.94	109.44 $\pm$ 6.73
Standing on one leg		
ROM of the knee joint angles (degrees)		
Left knee	33.59 $\pm$ 27.37	36.11 $\pm$ 29.48
Right knee	80.67 $\pm$ 24.78	73.97 $\pm$ 21.93

Table 6.6 shows the virtual challenge scores for each trial of both the motor tasks, entering in the bathtub and standing on one leg inside the bathtub, of the virtual challenge Take a Shower.

Table 6.6 - Number of times the user kicked the bathtub rim, and sound playing duration inside bathtub (s) in each trial of entering in the bathtub and standing on one leg inside the bathtub, respectively, in virtual challenge "Take a Shower"

Virtual challenge scores				
Participants	Number of times the user kicked the bathtub rim		Sound playing duration inside bathtub (s)	
	T1	T2	T1	T2
P1	21	1	10.00	4.53
P2	3	1	10.00	10.00
P3	5	1	2.58	10.00
P4	1	1	4.60	1.74
P5	0	0	10.00	10.00
P6	1	1	3.91	10.00

Based on Table 6.4, the statistical analysis for Take a Shower virtual challenge indicates no significant differences between T1 and T2. Despite this finding, most of the metrics evaluated showed an improvement in results. COM displacement, in both AP ($t = 0.267$) and ML ($t = 0.476$) directions, have decreased, indicating an improvement in the balance between trials, once the person is able to get inside the bathtub with smaller variations of the COM. Regarding the COM velocity, the decrease in the values

in the AP direction may indicate a greater care by the user to get inside the bath without touching the rim (to avoid falls) since the number of touches on the bathtub rim decreases considerably in some participants (Table 6.6).

In the motor task of standing on one leg (static motor task), the decrease in COM velocity in the AP direction for both sides of the axis (Table 6.4) indicate more stability. This can be evidenced by the rise in the time the sound played to the maximum value, between trials, in two participants (P3 e P4) (Table 6.6). None of the other assessment metrics showed improvements.

6.1.3 Cooking

Figure 6.3 shows the displacement of the COM in the AP direction relative to the ML direction in each trial while subjects collect food from the kitchen's shelves in the virtual challenge Cooking.

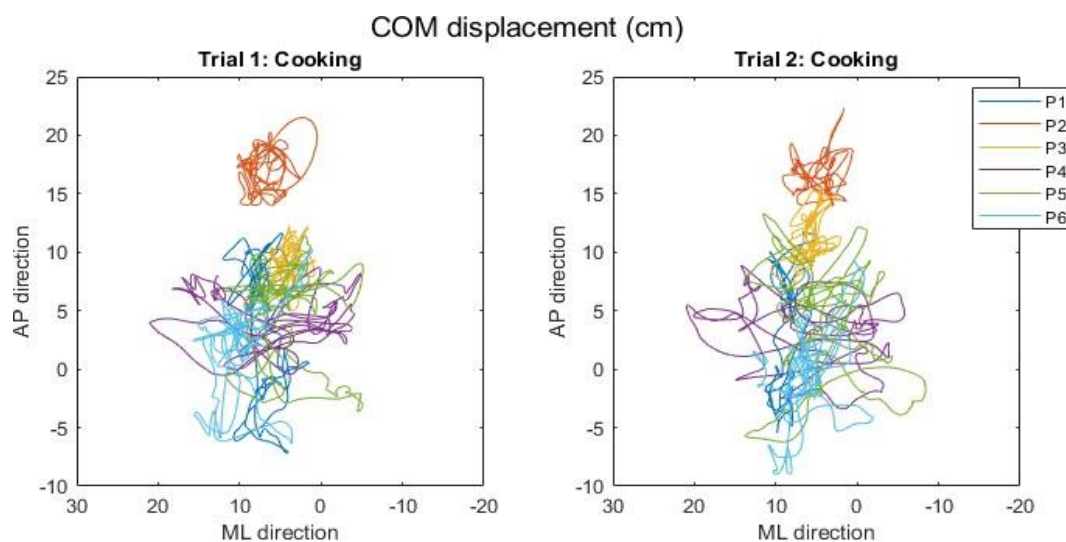


Figure 6.3 - COM displacement (cm) in the AP direction by the ML direction for all participants in each trial while collecting food from the kitchen shelves in the virtual challenge "Cooking".

After the construction of the Table 0.5 presented in Appendix I, the data was statistically evaluated, comparing the primary outcomes from T1 versus T2 for each virtual challenge. Table 6.7 presents the results of parametric metrics (paired samples t-test) and non-parametric metric (Wilcoxon signed-rank test) for the virtual challenge Take a Shower.

Table 6.7 - Mean and SD of T1 and T2, and the p-value of the paired samples test and Wilcoxon test for COM displacement (Disp) and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for collect the food of the kitchen shelves, of the virtual challenge “Cooking”, considering the time condition and a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Cooking	Paired Samples		Test Statistics ^a			
	Mean $\pm$ SD		Test		Wilcoxon	
	T1	T2	t	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Pick up the food						
DispAP_Cook	12.440 $\pm$ 2.064	13.992 $\pm$ 2.043	-1.862	.122	-	-
DispML_Cook	13.987 $\pm$ 2.881	14.550 $\pm$ 3.394	-.441	.677	-	-
VelMinAP_Cook	-8.737 $\pm$ 0.745	-8.265 $\pm$ 0.505	-.515	.628	-	-
VelMaxAP_Cook	11.008 $\pm$ 1.769	7.985 $\pm$ 0.857	-	-	-2.207 ^b	.027
VelMinML_Cook	-11.295 $\pm$ 1.665	-11.078 $\pm$ 1.844	-.245	.816	-	-
VelMaxML_Cook	11.378 $\pm$ 1.906	12.765 $\pm$ 2.338	-1.362	.231	-	-
a. Wilcoxon Signed Ranks Test						
b. Based on positive ranks						

Table 6.8 shows the virtual challenge scores for each trial of the virtual challenge Cooking.

Table 6.8 - Number of ingredients caught in kitchen's shelves in each trial of the virtual challenge “Cooking”

Participants	Number of ingredients caught in kitchen's shelves	
	T1	T2
P1	6	6
P2	6	6
P3	6	6
P4	6	6
P5	6	6
P6	6	6

Regarding the virtual challenge of collecting food from the kitchen selves (Cooking), the maximum COM velocity on the AP axis (VelMaxAP_Cook) (Table 6.5), forward direction, showed statistically significant differences between trials once the p -value (0.027) is lower than the significance level of 5 %. However, the mean and standard deviation indicate that COM velocity decreased from T1 (11.008 ± 1.769 cm/s) to T2 (7.985 ± 0.857 cm/s). This does not necessarily mean a regression once the condition of shelf depth and forward reach was not the aim of this motor task (the focus was lateral weightshifting). However, the COM velocity in backward direction (VelMinAP_Cook) (Table 6.3), where participants return to the starting position before choosing the next food, has increased between trials. Among the other variables, the COM velocity to the left side (VelMaxML_Cook) has increased noticeably from T1 (11.378 ± 1.906 cm/s) to T2 (12.765 ± 2.338 cm/s), contrarily to the COM velocity to the rightside, which presents a small decrease in module. The COM displacement for both AP and ML directions increased from T1 to T2 (Table 6.7), not presenting an improvement. Nonetheless, all the participants were able to collect all the six ingredients from the kitchen's shelves (Table 6.8).

6.1.4 Watch Tv

Figure 6.4 presents the participants' COM displacement in the AP direction relative to the ML direction in each trial during the three motor tasks of the virtual challenge Watch Tv: stand-to-sit, sit-to-stand, and walking.

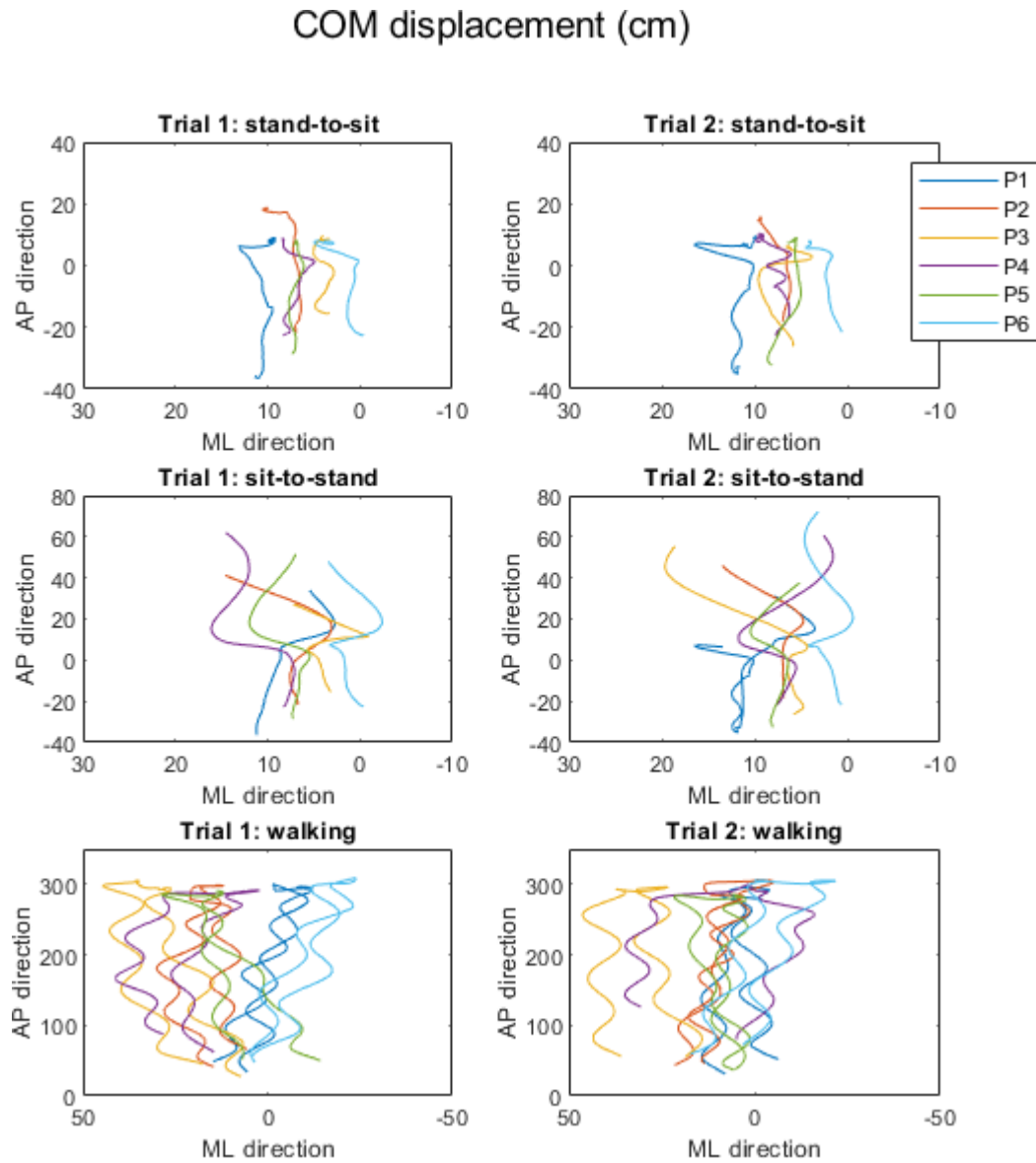


Figure 6.4 - COM displacement (cm) in the AP direction by the ML direction for all participants in each trial while performing the three motor tasks of the virtual challenge “Watch Tv”: stand-to-sit, sit-to stand, and walking.

After the construction of the Tables 0.6 to 0.8 presented in Appendix I, the data was statistically evaluated, comparing the primary outcomes from T1 versus T2 for each virtual challenge. Table 6.9 presents the results of parametric (paired samples *t*-test) and non-parametric metric (Wilcoxon signed-rank test) for the virtual challenge Watch Tv.

Table 6.9 - Mean and SD of T1 and T2,, and the p-value of the paired samples test and Wilcoxon test for COM displacement (Disp) and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for stand-to-sit, sit-to-stand, and walking motor tasks of the virtual challenge “Watch Tv”, considering the time condition and a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Watch TV	Paired Samples		Test Statistics ^a			
	Mean $\pm$ SD		Test		Wilcoxon	
	T1	T2	#test			
			t	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Stand-to-sit						
DispAP_Sit	35.080 $\pm$ 3.029	35.822 $\pm$ 2.398	-.367	.729	-	-
DispML_Sit	3.477 $\pm$ 0.551	4.532 $\pm$ 0.553	-	-	-1.153 ^c	.249
VelMinAP_Sit	-24.963 $\pm$ 3.934	-23.975 $\pm$ 1.270	-.235	.824	-	-
VelMaxAP_Sit	1.793 $\pm$ 0.295	1.713 $\pm$ 0.456	.146	.890	-	-
VelMinML_Sit	-5.540 $\pm$ 0.693	-6.422 $\pm$ 1.525	.576	.589	-	-
VelMaxML_Sit	4.333 $\pm$ 0.672	5.670 $\pm$ 1.419	-	-	-1.572 ^c	.116
Sit-to-stand						
DispAP_Stand	33.727 $\pm$ 3.080	33.950 $\pm$ 2.605	-.125	.906	-	-
DispML_Stand	3.373 $\pm$ 0.452	2.857 $\pm$ 0.414	1.281	.256	-	-
VelMinAP_Stand	0.897 $\pm$ 0.508	-0.740 $\pm$ 0.840	2.276	.072	-	-
VelMaxAP_Stand	32.327 $\pm$ 1.211	37.823 $\pm$ 3.182	-	-	-1.572 ^c	.116
VelMinML_Stand	3.860 $\pm$ 0.944	4.933 $\pm$ 1.012	-1.746	.141	-	-
VelMaxML_Stand	-5.705 $\pm$ 0.878	-4.102 $\pm$ 0.670	-1.531	.186	-	-
Walking						
DispAP_Walk	73.708 $\pm$ 3.391	77.713 $\pm$ 5.760	-	-	-1.153 ^c	.249
DispML_Walk	9.113 $\pm$ 0.982	7.483 $\pm$ 0.553	2.587	.049	-	-
VelMinAP_Walk	42.647 $\pm$ 3.259	46.773 $\pm$ 3.836	-3.381	.020	-	-
VelMaxAP_Walk	64.854 $\pm$ 3.830	70.702 $\pm$ 4.675	-2.571	.050	-	-
VelMinML_Walk	-20.338 $\pm$ 1.881	-20.137 $\pm$ 1.330	-.105	.921	-	-
VelMaxML_Walk	18.360 $\pm$ 3.261	17.202 $\pm$ 2.438	-	-	-.734 ^b	.463
a. Wilcoxon Signed Ranks Test						
b. Based on positive ranks						
c. Based on negative ranks						

Table 6.10 shows the mean and SD of the secondary outcomes of all the participants, for each trial of the virtual challenge Watch Tv, namely, ROM of left and right knee joint angles on the sagittal plane (degrees) during stand-to-sit, sit-to-stand, and walking, and spatiotemporal gait parameters such as stride length (cm) and stride time (s) for walking motor task.

Table 6.10 – Mean and SD of the ROM of the left and right knee joint angles on the sagittal plane (degrees) for stand-to-sit, sit-to-stand, and walking motor tasks, and the stride length (cm) and stride time (s) for walking motor task in each trial of the virtual challenge “Watch Tv”

Secondary Outcomes	Mean $\pm$ SD	
	T1	T2
Stand-to-sit		
ROM of the knee joint angles (degrees)		
Left knee	77.70 $\pm$ 11.63	79.12 $\pm$ 11.24
Right knee	79.66 $\pm$ 10.91	80.30 $\pm$ 12.90
Sit-to-stand		
ROM of the knee joint angles (degrees)		
Left knee	71.66 $\pm$ 10.46	70.22 $\pm$ 9.49
Right knee	74.18 $\pm$ 10.88	72.89 $\pm$ 11.44
Walking		
ROM of the knee joint angles (degrees)		
Left knee	52.60 $\pm$ 3.50	54.51 $\pm$ 5.02
Right knee	52.67 $\pm$ 3.16	54.89 $\pm$ 8.65
Spatiotemporal gait parameters		
Stride length (cm)	73.62 $\pm$ 7.90	78.98 $\pm$ 13.12
Stride time (s)	1.43 $\pm$ 0.16	1.38 $\pm$ 0.16

Table 6.11 presents the virtual challenge scores for each trial of the virtual challenge Watch Tv.

Table 6.11 – Television state achieved in each trial of the virtual challenge “Watch Tv”

Participants	Television state achieved	
	T1	T2
P1	On	On
P2	On	On
P3	On	On
P4	On	On
P5	On	On
P6	On	On

Concerning the virtual challenge “Watch Tv”, none of the stand-to-sit and sit-to-stand motor tasks presented statistically significant differences between trials once the p -value is higher than 0.05 (Table 6.9). For these two motor tasks, improvements were found for COM displacement in the ML axis (DispML_Stand), and maximum COM velocity in AP (VelMaxAP_Stand) and ML (VelMaxML_Stand) directions. For these three-assessment metrics, in general, participants showed an increase in balance in the ML axis (with decreasing values from T1 to T2), an increase in velocity in forward movements, and a decrease in velocity in lateral movements, while performing the task from sitting to standing.

Regarding the walking motor task, two variables (DispML_Walk, and VelMinAP_Walk) showed statistically significant differences between first and second trials (p -value = 0.049, and p -value = 0.020, respectively) (Table 6.9). These results suggest a significant improvement in balance in the ML direction since the COM displacement in this axis decreased considerably from T1 (9.113 ± 0.982 cm) to T2 (7.483 ± 0.553 cm), and that participants were able to walk significantly faster in the direction of movement in the second trial (46.773 ± 3.836 cm/s) compared to the first one (42.647 ± 3.259 cm/s) since the minimum COM velocity in the AP axis increased. The decreasing of the stride time (Table 6.10) reinforces this statement. Although the other variables for this motor task did not reveal statistically significant differences between trials, all of them presented an improvement in balance function. COM displacement in the AP direction (DispAP_Walk) increased between trials, meaning that in the second trial participants were able to perform a greater COM displacement in this direction (77.713 ± 5.760 cm), which indicates a greater distance achieved during a gait cycle compared to the first trial (73.708 ± 3.391) (Table 6.9). This explanation can be supported by the increase of the stride length values, showed in Table 6.10. The maximum COM velocity in AP axis, presenting positive values, also increased (Table 6.9), complementing the explanation of the participants’ faster velocity in this direction. The COM velocity

for left (VelMaxML_Walk) and right (VelMinML_Walk) sides of ML direction decreased from T1 to T2 (Table 6.9), meaning more stable movements to the sides while walking forwards. All the participants were able to turn on the television (Table 6.11).

None of the studies reviewed in the literature assesses the user's performance during the VR training. Thus, it is impossible to perform a comparison between the VR training data from the present study with those from the literature.

6.2 Before vs after VR intervention

From data acquisition trials carried out before and after VR intervention, primary and secondary outcome measures for the BBS and TUG clinical tests were computed (Table 0.9 to Table 0.14, Appendix I). These outcomes were statistically evaluated, comparing the primary outcomes from before versus after VR intervention for each BBS's and TUG's task.

Tables 6.12 and 6.13 present the results of parametric (paired samples *t*-test) and non-parametric metrics (Wilcoxon signed-rank test) test, for BBS's and TUG's tasks, respectively.

Table 6.12 - Mean and SD of pre and post VR training trials, and the p-value of the paired samples test and Wilcoxon test for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for BBS' tasks, considering the time condition and a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

BBS	Paired Samples				Test Statistics ^a	
	Mean $\pm$ SD		Test		Wilcoxon	
	Pre	Post	t	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Sit-to-stand						
DispAP_BBS1	42.235 $\pm$ 1.445	37.548 $\pm$ 2.344	2.629	.047	-	-
DispML_BBS1	2.573 $\pm$ 0.229	2.550 $\pm$ 0.426	.049	.962	-	-
VelMinAP_BBS1	-6.917 $\pm$ 1.502	-10.002 $\pm$ 4.041	-	-	-.105 ^c	.917
VelMaxAP_BBS1	48.117 $\pm$ 2.860	38.878 $\pm$ 8.081	1.444	.208	-	-
VelMinML_BBS1	-3.913 $\pm$ 0.631	-3.523 $\pm$ 0.680	-1.088	.326	-	-
VelMaxML_BBS1	2.910 $\pm$ 0.819	4.030 $\pm$ 0.800	-1.477	.200	-	-
Standing unsupported						
DispAP_BBS2	2.200 $\pm$ 0.312	2.362 $\pm$ 0.510	-	-	-.524 ^c	.600
DispML_BBS2	0.822 $\pm$ 0.117	0.912 $\pm$ 0.111	-.519	.626	-	-
VelMinAP_BBS2	-1.990 $\pm$ 0.627	-2.203 $\pm$ 0.706	-	-	-.524 ^b	.600
VelMaxAP_BBS2	1.108 $\pm$ 0.152	1.137 $\pm$ 0.255	-.155	.883	-	-
VelMinML_BBS2	-1.057 $\pm$ 0.496	-1.440 $\pm$ 0.522	-	-	-1.156 ^b	.248
VelMaxML_BBS2	0.705 $\pm$ 1.131	0.642 $\pm$ 0.056	.423	.690	-	-
Sitting unsupported						
DispAP_BBS3	1.647 $\pm$ 0.408	1.382 $\pm$ 0.111	-	-	-.314 ^c	.753
DispML_BBS3	1.118 $\pm$ 0.347	0.705 $\pm$ 0.162	1.122	.313	-	-
VelMinAP_BBS3	-5.513 $\pm$ 1.652	-5.135 $\pm$ 1.399	-.924	.398	-	-
VelMaxAP_BBS3	6.375 $\pm$ 2.613	6.880 $\pm$ 3.237	-.305	.773	-	-
VelMinML_BBS3	-3.167 $\pm$ 0.625	-2.240 $\pm$ 0.511	-2.096	.090	-	-
VelMaxML_BBS3	1.303 $\pm$ 0.644	2.335 $\pm$ 0.907	-	-	-1.782 ^b	.075

BBS			Paired Samples Test		Test Statistics ^a	
	Mean $\pm$ SD		t-test		Wilcoxon	
	Pre	Post	<i>t</i>	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Stand-to-sit						
DispAP_BBS4	40.058 $\pm$ 1.844	35.810 $\pm$ 2.045	3.969	.011	-	-
DispML_BBS4	3.950 $\pm$ 0.898	3.067 $\pm$ 0.685	1.659	.158	-	-
VelMinAP_BBS4	-39.522 $\pm$ 4.125	-38.225 $\pm$ 4.337	-.351	.740	-	-
VelMaxAP_BBS4	2.472 $\pm$ 0.453	3.663 $\pm$ 0.631	-2.729	.041	-	-
VelMinML_BBS4	-5.257 $\pm$ 1.570	-4.520 $\pm$ 1.064	-.559	.600	-	-
VelMaxML_BBS4	2.307 $\pm$ 0.363	2.413 $\pm$ 0.331	-.178	.866	-	-
Transfers						
DispAP_BBS5	95.915 $\pm$ 3.175	95.400 $\pm$ 4.164	.168	.874	-	-
DispML_BBS5	13.653 $\pm$ 1.605	12.683 $\pm$ 0.964	.565	.597	-	-
VelMinAP_BBS5	-38.720 $\pm$ 2.442	-41.933 $\pm$ 2.678	3.004	.030	-	-
VelMaxAP_BBS5	43.570 $\pm$ 3.222	46.175 $\pm$ 4.696	-.846	.436	-	-
VelMinML_BBS5	-17.305 $\pm$ 0.811	-19.795 $\pm$ 1.562	2.148	.084	-	-
VelMaxML_BBS5	19.380 $\pm$ 0.487	18.297 $\pm$ 2.408	-	-	-.105 ^c	.917
Standing with eyes closed						
DispAP_BBS6	1.390 $\pm$ 0.244	1.435 $\pm$ 0.209	-.182	.862	-	-
DispML_BBS6	0.513 $\pm$ 0.094	0.685 $\pm$ 0.147	-1.478	.199	-	-
VelMinAP_BBS6	-2.017 $\pm$ 0.610	-1.635 $\pm$ 0.576	-3.452	.018	-	-
VelMaxAP_BBS6	1.090 $\pm$ 0.179	1.270 $\pm$ 1.184	-3.286	.022	-	-
VelMinML_BBS6	-1.190 $\pm$ 0.585	-0.905 $\pm$ 0.252	-	-	-.734 ^b	.463
VelMaxML_BBS6	0.557 $\pm$ 0.089	0.673 $\pm$ 0.151	-1.159	.299	-	-

BBS	Paired Samples		Test Statistics ^a			
	Test					
	Mean $\pm$ SD		<i>t</i> test		Wilcoxon	
	Pre	Post	<i>t</i>	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Standing with feet together						
DispAP_BBS7	2.010 $\pm$ 0.330	2.275 $\pm$ 0.491	-.804	.458	-	-
DispML_BBS7	1.313 $\pm$ 0.093	1.565 $\pm$ 0.145	-	-	-1.992 ^c	.046
VelMinAP_BBS7	-2.100 $\pm$ 0.732	-2.583 $\pm$ 0.648	.763	.480	-	-
VelMaxAP_BBS7	1.093 $\pm$ 0.165	1.162 $\pm$ 0.154	-.465	.662	-	-
VelMinML_BBS7	-1.088 $\pm$ 0.177	-1.187 $\pm$ 0.233	.462	.663	-	-
VelMaxML_BBS7	1.143 $\pm$ 0.174	1.792 $\pm$ 0.517	-	-	-1.992 ^c	.046
Reaching forward						
DispAP_BBS8	9.773 $\pm$ 0.949	8.365 $\pm$ 0.934	6.890	.001	-	-
DispML_BBS8	3.200 $\pm$ 0.533	3.178 $\pm$ 0.474	.026	.980	-	-
VelMinAP_BBS8	-11.645 $\pm$ 0.956	-8.870 $\pm$ 1.391	-2.042	.097	-	-
VelMaxAP_BBS8	7.077 $\pm$ 1.128	8.023 $\pm$ 1.009	-1.395	.222	-	-
VelMinML_BBS8	-2.770 $\pm$ 0.335	-3.337 $\pm$ 0.647	-	-	-.734 ^b	.463
VelMaxML_BBS8	3.853 $\pm$ 0.597	3.743 $\pm$ 0.875	.082	.938	-	-
Pick up an object						
DispAP_BBS9	6.600 $\pm$ 0.928	5.560 $\pm$ 0.832	1.370	.229	-	-
DispML_BBS9	3.762 $\pm$ 0.978	3.380 $\pm$ 1.101	.815	.452	-	-
VelMinAP_BBS9	-7.602 $\pm$ 0.888	-6.563 $\pm$ 1.324	-.598	.576	-	-
VelMaxAP_BBS9	7.013 $\pm$ 0.773	6.950 $\pm$ 1.271	.075	.943	-	-
VelMinML_BBS9	-4.057 $\pm$ 0.670	-4.000 $\pm$ 0.873	-.140	.894	-	-
VelMaxML_BBS9	4.240 $\pm$ 0.861	4.797 $\pm$ 0.761	-.694	.519	-	-

BBS	Paired Samples		Test Statistics ^a			
	Test					
	Mean $\pm$ SD		<i>t</i> test		Wilcoxon	
	Pre	Post	<i>t</i>	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Looking over shoulders						
DispAP_BBS10	3.677 $\pm$ 0.438	3.717 $\pm$ 0.215	-.139	.895	-	-
DispML_BBS10	2.335 $\pm$ 0.324	2.912 $\pm$ 0.395	-1.121	.313	-	-
VelMinAP_BBS10	-3.200 $\pm$ 0.667	-3.727 $\pm$ 0.539	-	-	-1.363 ^b	.173
VelMaxAP_BBS10	3.208 $\pm$ 0.486	3.780 $\pm$ 0.539	-1.445	.208	-	-
VelMinML_BBS10	-3.018 $\pm$ 0.389	-3.132 $\pm$ 0.377	.189	.858	-	-
VelMaxML_BBS10	2.458 $\pm$ 0.360	4.037 $\pm$ 0.552	-2.526	.053	-	-
Turn 360 degrees						
DispAP_BBS11	21.392 $\pm$ 2.707	20.437 $\pm$ 2.482	.265	.801	-	-
DispML_BBS11	22.605 $\pm$ 1.610	21.595 $\pm$ 1.820	.418	.694	-	-
VelMinAP_BBS11	-27.698 $\pm$ 3.648	-29.243 $\pm$ 2.805	.363	.731	-	-
VelMaxAP_BBS11	26.020 $\pm$ 3.104	23.132 $\pm$ 1.501	.807	.457	-	-
VelMinML_BBS11	-25.968 $\pm$ 2.229	-22.338 $\pm$ 1.452	-1.111	.317	-	-
VelMaxML_BBS11	32.145 $\pm$ 3.925	25.462 $\pm$ 1.605	2.064	.094	-	-
Place alternate foot on step						
DispAP_BBS12	6.770 $\pm$ 0.542	7.402 $\pm$ 0.836	-.530	.619	-	-
DispML_BBS12	16.312 $\pm$ 0.772	15.590 $\pm$ 0.129	-	-	-.314 ^b	.753
VelMinAP_BBS12	-8.037 $\pm$ 0.368	-7.393 $\pm$ 0.655	-1.264	.262	-	-
VelMaxAP_BBS12	9.703 $\pm$ 0.834	9.185 $\pm$ 0.907	.791	.465	-	-
VelMinML_BBS12	-19.775 $\pm$ 1.755	-19.087 $\pm$ 0.800	-	-	-.315 ^c	.752
VelMaxML_BBS12	20.133 $\pm$ 1.261	19.910 $\pm$ 0.772	.148	.888	-	-

BBS	Paired Samples		Test Statistics ^a			
	Test					
	Mean ± SD		#test		Wilcoxon	
	Pre	Post	<i>t</i>	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Standing with one foot in front						
DispAP_BBS13	1.630 ± 0.333	1.745 ± 0.173	-.291	.783	-	-
DispML_BBS13	1.943 ± 0.343	1.780 ± 0.098	-	-	-.943 ^b	.345
VelMinAP_BBS13	-2.052 ± 0.622	-2.342 ± 0.613	-	-	-.524 ^b	.600
VelMaxAP_BBS13	1.730 ± 0.551	2.140 ± 0.758	-	-	-.943 ^c	.345
VelMinML_BBS13	-1.418 ± 0.114	-1.667 ± 0.296	.998	.364	-	-
VelMaxML_BBS13	1.888 ± 0.265	2.535 ± 0.735	-.932	.394	-	-
Standing on one leg						
DispAP_BBS14	4.508 ± 0.707	4.962 ± 0.805	-	-	-.524 ^c	.600
DispML_BBS14	9.367 ± 1.690	9.083 ± 1.068	.262	.804	-	-
VelMinAP_BBS14	-3.853 ± 0.670	-2.853 ± 0.471	-2.943	.032	-	-
VelMaxAP_BBS14	6.287 ± 1.656	7.005 ± 0.916	-.376	.723	-	-
VelMinML_BBS14	-9.307 ± 2.760	-8.467 ± 2.769	-.803	.459	-	-
VelMaxML_BBS14	9.520 ± 2.579	7.417 ± 1.974	.771	.476	-	-
a. Wilcoxon Signed Ranks Test						
b. Based on positive ranks						
c. Based on negative ranks						

Table 6.13 - Mean and SD of T1 and T2, and the p-value of the paired samples test and Wilcoxon test for COM displacement (Disp) and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for sit-to-stand, walking, and stand-to-sit motor tasks of TUG, considering the time condition and a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

TUG	Paired Samples		Test Statistics ^a			
	Mean $\pm$ SD		Test		Wilcoxon	
	Pre	Post	t	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Sit-to-stand						
DispAP_Stand	38.928 $\pm$ 3.046	37.310 $\pm$ 3.122	.782	.470	-	-
DispML_Stand	5.207 $\pm$ 0.711	5.227 $\pm$ 0.842	-.021	.984	-	-
VelMinAP_Stand	-5.222 $\pm$ 1.704	-6.020 $\pm$ 1.714	.802	.459	-	-
VelMaxAP_Stand	50.185 $\pm$ 4.329	47.108 $\pm$ 3.848	.960	.381	-	-
VelMinML_Stand	-6.865 $\pm$ 1.908	-8.640 $\pm$ 4.153	-	-	-.105 ^c	.917
VelMaxML_Stand	10.277 $\pm$ 3.422	9.408 $\pm$ 2.309	.247	.815	-	-
Walking						
DispAP_Walk	115.265 $\pm$ 2.603	113.800 $\pm$ 2.035	1.147	.303	-	-
DispML_Walk	15.330 $\pm$ 2.321	15.270 $\pm$ 2.271	.025	.981	-	-
VelMinAP_Walk	85.905 $\pm$ 3.447	84.233 $\pm$ 3.741	1.479	.199	-	-
VelMaxAP_Walk	120.197 $\pm$ 3.172	113.738 $\pm$ 3.866	2.617	.047	-	-
VelMinML_Walk	-18.453 $\pm$ 3.470	-22.898 $\pm$ 4.488	1.104	.320	-	-
VelMaxML_Walk	17.775 $\pm$ 4.525	11.605 $\pm$ 4.601	-	-	-1.572 ^b	.116
Stand-to-sit						
DispAP_Sit	34.670 $\pm$ 2.331	36.375 $\pm$ 3.047	-1.159	.299	-	-
DispML_Sit	5.095 $\pm$ 1.144	5.963 $\pm$ 0.908	-.622	.561	-	-
VelMinAP_Sit	-35.328 $\pm$ 2.764	-36.767 $\pm$ 2.955	1.476	.200	-	-
VelMaxAP_Sit	1.813 $\pm$ 0.266	1.622 $\pm$ 0.347	.554	.604	-	-
VelMinML_Sit	-11.137 $\pm$ 3.630	-12.022 $\pm$ 2.256	.164	.876	-	-
VelMaxML_Sit	5.520 $\pm$ 2.403	5.368 $\pm$ 1.882	-	-	-.524 ^c	.600
a. Wilcoxon Signed Ranks Test						
b. Based on positive ranks						
c. Based on negative ranks						

Table 6.14 shows the mean and SD of the secondary outcomes of BBS clinical scale before and after VR training namely, ROM of left and right knee joint angles on the sagittal plane (degrees) during sit-to-stand, stand-to-sit, place alternate foot on step, and standing on one leg, and the maximum hand forward position (cm) for reaching forward.

Table 6.14 - Mean and SD of the ROM of the left and right knee joint angles on the sagittal plane (degrees) for sit-to-stand, stand-to-sit, place alternate foot on step, and standing on one leg, and the maximum hand position (cm) for reaching forward BBS's tasks

Secondary Outcomes BBS	Mean $\pm$ SD	
	Pre	Post
Sit-to-stand		
ROM of the knee joint angle (degrees)		
Left knee	77.41 $\pm$ 11.15	79.01 $\pm$ 10.92
Right knee	78.57 $\pm$ 12.39	80.44 $\pm$ 12.50
Stand-to-sit		
ROM of the knee joint angles (degrees)		
Left knee	75.69 $\pm$ 10.89	78.82 $\pm$ 11.54
Right knee	78.11 $\pm$ 11.13	80.16 $\pm$ 11.81
Place alternate foot on step		
ROM of the knee joint angles (degrees)		
Left knee	71.92 $\pm$ 6.13	75.34 $\pm$ 9.12
Right knee	70.08 $\pm$ 7.53	75.72 $\pm$ 10.60
Standing on one leg		
ROM of the knee joint angles (degrees)		
Left knee	48.64 $\pm$ 44.21	52.09 $\pm$ 41.82
Right knee	38.53 $\pm$ 29.80	43.33 $\pm$ 36.59
Reaching forward		
Maximum hand position (cm)	67.65 $\pm$ 5.34	67.06 $\pm$ 5.51

Table 6.15 shows the mean and SD of the secondary outcomes the TUG clinical scale before and after VR training, namely, ROM of left and right knee joint angles on the sagittal plane (degrees) during sit-to-stand, walking, and stand-to-sit, and spatiotemporal gait parameters such as stride length (cm) and stride time (s) for walking motor task.

Table 6.15 - Mean and SD of the ROM of the left and right knee joint angles on the sagittal plane (degrees) for sit-to-stand, walking and stand-to-sit motor tasks, and the stride length (cm) and stride time (s) for walking motor task in each trial of TUG clinical scale

Secondary Outcomes TUG	Mean $\pm$ SD	
	Pre	Post
Sit-to-stand		
ROM of the knee joint angles (degrees)		
Left knee	55.55 $\pm$ 15.49	60.82 $\pm$ 3.74
Right knee	58.97 $\pm$ 13.52	63.94 $\pm$ 10.68
Walking		
ROM of the knee joint angles (degrees)		
Left knee	62.27 $\pm$ 2.09	61.26 $\pm$ 2.40
Right knee	62.73 $\pm$ 6.44	62.93 $\pm$ 5.57
Spatiotemporal gait parameters		
Stride length (cm)	114.82 $\pm$ 6.55	115.89 $\pm$ 4.81
Stride time (s)	1.16 $\pm$ 0.09	1.19 $\pm$ 0.09
Stand-to-sit		
ROM of the knee joint angles (degrees)		
Left knee	62.27 $\pm$ 13.60	67.99 $\pm$ 7.44
Right knee	62.11 $\pm$ 16.19	66.17 $\pm$ 11.02

By clinically analysing the BBS and TUG tests, before and after the VR intervention, it was possible to obtain the final score of each participant, for both tests (Table 6.16).

Table 6.16 – Final scores for BBS and TUG clinical tests, for each of the participants, before and after the VR intervention

Final Score	BBS		TUG (s)	
	Before	After	Before	After
P1	56	56	10.32	10.17
P2	56	56	12.00	10.37
P3	55	55	12.55	12.32
P4	56	56	9.87	10.64
P5	56	56	9.90	9.00
P6	56	56	9.40	10.38

The Kolmogorov-Smirnov test (Table 0.21, Appendix II) indicates that the BBS metrics do not follow a normal distribution; thus, for the BBS metrics, the Wilcoxon signed-rank test was applied. On the other hand, metrics from TUG test (Table 0.28, Appendix II) were evaluated according to the *t*-test. Table 6.17 shows the mean and SD of BBS and TUG before and after the VR training, as well as their *p*-value resulting from the statistical analyses.

Table 6.17 - Mean and SD for pre and post VR training, the *p*-value of the paired samples test, and the *p*-value of the Wilcoxon test for BBS and TUG clinical tests, considering the time condition and a significance level of 5 %

	Paired-Sample T-test				Test Statistics ^a	
	Mean $\pm$ SD		<i>t</i> -test		Wilcoxon	
	Pre	Post	<i>t</i>	Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
BBS	55.830 $\pm$ 0.167	55.830 $\pm$ 0.167	—	—	.000 ^b	1.000
TUG	10.673 $\pm$ 0.525	10.480 $\pm$ 0.437	.480	.652	—	—

a. Wilcoxon Signed Ranks Test

b. The sum of negative ranks equals the sum of positive ranks

Comparing the scores of the clinical assessment done by the clinical tests BBS and TUG, before and after the VR training, in general, none of them showed statistically significant differences since the *p*-value is higher than the significance level of 5 % (Table 6.17). However, the TUG presented improved results after VR training as the time used to perform the task decreased from 10.673 $\pm$ 0.525 s to 10.480 $\pm$ 0.437 s. These values are at the threshold of the classification of a person presenting independence in mobility and balance for healthy individuals. BBS maintained the same score before and after training (55.830 $\pm$ 0.167), since the only participant (P3) who did not have a maximum score, kept the same result. Probably with more VR training sessions, P3 would be able to achieve the maximum score. Statistically significant differences between the BBS and TUG clinical tests before and after VR training have been found in the literature [24]–[27]. These results may be due to the fact that the studies included post-stroke patients who have a large range of progression, in contrast to the healthy participants in the present study. In addition, the studies usually include more than just one VR session, which may also have positive effects on the results.

Although the clinical score assigned to the BBS test was maintained, the statistical results of the COM displacement and COM velocity are slightly different, allowing better conclusions about eventual improvements. Based on Table 6.12, the COM displacement in AP direction for the first (DispAP_BBS1) and fourth BBS tasks (DispAP_BBS4), the maximum COM velocity in the AP axis for fourth BBS task

(VelMaxAP_BBS4), the minimum COM velocity in the AP direction for BBS fifth task (VelMinAP_BBS5), the minimum and maximum COM velocity in AP axis for BBS sixth task (VelMinAP_BBS6, and VelMaxAP_BBS6, respectively), the COM displacement in AP axis for BBS task number eight (DispAP_BBS8), the minimum COM velocity in AP direction for BBS task number fourteen (VelMinAP_BBS14), as well as for COM displacement and maximum COM velocity in the ML direction for BBS task number seven (DispML_BBS7, and VelMaxML_BBS7, respectively), showed statistically significant differences between trials performed before and after VR training, since their p-value is lower than the significance level of 5 %.

Looking more carefully at these metrics, in BBS sit-to-stand task (BBS1), the decrease in COM displacement in the AP direction (p -value = 0.047) (Table 6.12) means that after VR training participants were able to perform the sit-to-stand task with a smaller COM variation, indicating greater stability of the movement. This decrease was also verified for ML direction, although not significant. Moreover, in the stand-to-sit motor task (BBS4), there was also a significant decrease in COM displacement in the AP direction (p -value = 0.011) (Table 6.12), indicating that also for this task, participants were able to perform the motor task with more stability. Further, for ML direction, the COM displacement presented a decrease, although not significant. The significant increase in maximum COM velocity in the same direction (p -value = 0.041), represents a faster forward movement in the stand-to-sit task, probably when participants lean, before they sit.

When performing transfers between chairs (BBS5), participants have shown a statistically significant improvement in minimum COM velocity (p -value = 0.030) after VR training (Table 6.12), accompanied by a decrease of COM displacement on both AP and ML directions, although not significant. These findings indicate that the participants, after VR training, were not only able to perform this motor task faster, but also with more balance.

While standing with eyes closed (BBS6), after VR training, participants showed a statistically significant difference, when compared to after VR training, of the minimum (p -value = 0.018) and maximum (p -value = 0.022) COM velocity in the AP direction (Table 6.12). The first result indicates an improvement since the participants performed slower backward movements; however, the second shows a worsening of the metric as the forward movements were faster. Cho et al. [27] also showed improvements in postural sway velocity (similar to COM velocity) in the AP direction, although not significant. The same occurred for the ML direction. Moreover, for the motor task of standing with feet together (BBS7), participants have also shown statistically significant differences in COM displacement and maximum COM velocity in the ML direction, although not positive (Table 6.12). For the second BBS

motor task (standing unsupported with eyes open) no statistically significant differences were found, despite the improvement of the COM velocity in the ML direction, as verified in some literature studies [25], [27]. Although not significant, the same studies present improvements in the AP direction too. Moreover, literature studies have shown a statistically significant difference in the AP and ML oscillation of the COP (difference from this project) in static balance with both eyes open and closed (similar to BBS2 and BBS6, respectively) [24]. These non-positive results in this project may be due to the fact that these motor tasks were not directly trained in the virtual challenges applied during VR intervention.

For the BBS motor task of reaching forward (BBS8), despite the clinical score being the same, according to Table 6.12 it is possible to verify that after VR training, the participants were able to perform the same movement with greater stability and balance, since the COM displacement significantly decreased in AP direction (p -value = 0.001). In addition, although not significant, participants were not only capable to realize the task with more stability but also faster with the increase of the maximum COM velocity in the same axis.

According with Table 6.12, participants showed a statistically significant difference for the motor task of standing on one leg (p -value = 0.032), presenting a smaller value to minimum COM velocity in the AP direction.

For the other tasks, improvements were also observed, although not significant, as follows. The COM displacement decreased for both AP and ML directions while sitting (BBS3), picking an object from the floor (BBS9), and turning 360 degrees (BBS11). Further, it was reported a decrease in COM displacement in the ML directions in activities that are prone to greater imbalances in this direction such as placing alternate foot on step (BBS12), standing with one foot in front of the other (BBS13), and standing on one leg (BBS14) (Table 6.12).

Regarding TUG, only the maximum velocity of COM in AP direction from walking motor task presented statistically significant differences before and after VR training (Table 6.13). However, this difference means a decrease in maximum velocity, which is in accordance with the stride time values available in Table 6.15. This event may be related to the reduced space to walk (3 meters each way) making it impossible for people to increase speed much, giving priority to a slower and more stable gait. In addition to this metric, the COM displacement in ML direction decreased meaning a more stabilized walking. Furthermore, stride length showed improvements between pre- and post- VR training (no statistical tests were performed for the secondary results), as well as verified in some studies reviewed in the literature that showed statistically significant differences between pre- and post- training [26], [27], [30], [34]. These results may be due to the fact that the studies in the literature included post-stroke

patients, with a wide range of progression, by contrast to the healthy participants included in this project. The sit-to-stand motor task also showed improvements in COM displacement in the ML direction, and in the maximum COM velocity in the same axis, indicating that participants carried out less and slower movements in this direction, which suggests more stability (Table 6.13). For the stand-to-sit motor task, improvements in COM velocity were found in AP direction, with higher velocity values backwards (sitting direction), and smaller velocity values in the opposite direction to the sitting movement (forwards). Also, the maximum COM velocity in the ML direction has decreased, showing improvements for the same reason mentioned above.

6.3 User's experience evaluation

The performed user's experience evaluation tests aim to evaluate the VR tool in terms of the realism of the VREs and how engaged the participant feels by them (IPQ questionnaire), and the experience lived by the user while using it to complete the virtual tasks (IMI questionnaire).

Figure 0.1 (Appendix III) presents the results of IPQ questionnaire per participant. Table 6.18 indicates the mean and SD of each factor of the IPQ and the maximum possible score for each sub-scale. Results showed that participants felt a higher presence as transportation (Spatial Presence) with 4.25 mean value, followed by the Experienced Realism (3.88 of mean), and then Involvement (3.50 of mean), meaning that the user. Participants' highest compliance was found for Experienced Realism (with a SD of 0.24) and for Global Presence (with a SD of 0.24), suggesting that participants have an identical sense of presence in the VRE of this tool, with a score of 3.90.

Table 6.18 - Mean and standard deviation (SD) of all the participants, for each factor of IPQ

IPQ				
	Spatial Presence	Involvement	Experienced Realism	Global Presence
Mean $\pm$ SD	4.25 $\pm$ 0.53	3.58 $\pm$ 0.45	3.88 $\pm$ 0.24	3.90 $\pm$ 0.24
Best score	6.33	6.00	7.00	6.44

Figure 0.2 (Appendix III) shows the subject's answer to the IMI questionnaire. Table 6.19 presents the mean and SD of each subscale of the IMI questionnaire. Table 6.20 presents the participants' answers for the three open-ended questions. Table 6.19 suggests that participants felt a higher Interest/Enjoyment (5.81 of mean), proving the high acceptability of the tool, and felt highly competent while performing the virtual challenges (mean of 5.53 in Perceived Competence). In addition, participants also felt that the tool has great Value and Usefulness for improving the balance by reporting, for example, that the tool helps

them to understand their limitations in posture and balance (P6), as well as to increase balance and trunk mobility (P5), and also to recover from physical injuries of the lower body (P4). Despite the high Effort/Importance experienced by the participants, they reported feeling no Pressure/Tension (3.03 of mean) while performing the virtual challenges.

Table 6.19 - Mean and standard deviation (SD) of all the participants, for each subscale of IMI

IMI					
	Interest/ Enjoyment	Perceived Competence	Effort/ Importance	Pressure/ Tension	Value/ Usefulness
Mean $\pm$ SD	5.81 $\pm$ 0.61	5.53 $\pm$ 0.58	5.27 $\pm$ 0.98	3.03 $\pm$ 1.53	5.33 $\pm$ 0.84
Best score	7.00	7.00	2.20	1.00	7.00

Table 6.20 - Participants' answers to the open questions of the Value/Usefulness subscale of IMI questionnaire

Open-ended questions of Value/Usefulness subscale			
	"I think that doing this activity is useful for..."	"I think is important to do because it can..."	"I think doing this activity could help me to..."
P1	"improving my balance"	"improving my balance"	"improving my balance"
P2	"practice certain motor skills on injured patients, or patients suffering from some illness that restricts their movement"	"help recover motor skills in controlled environments"	"recover from physical injuries to the lower body"
P3	"people with movements constraints"	"develop specific movements"	"exercise, practise and develop some movements that are hard for me to do"
P4	"retrain people after some accident or illness"	"help people with motor difficulties"	"improve my equilibrium and stability"
P5	"training balance and mobility"	"prompt self-awareness about balance, mobility and maybe ways to improve it"	"improve balance, focus and trunk mobility"
P6	"evaluate the progress of people with postural and stability deficits."	"improve the stability, postural, and balance performance of people with balance losses."	"understand my postural and balance limits."

6.4 Conclusions

During VR intervention, VelMaxAP_Cook (p -value = 0.027), DispML_Walk (p -value = 0.049), and VelMinAP_Walk (p -value = 0.020) are the only variables presenting statistically significant differences between the first and second trial of VR intervention. The lack of more significant differences between trials may be because the participants were all healthy and the reduced number of trials and VR sessions. By comparing the balance performance before and after the VR intervention, statistically significant differences were found for the following BBS's tasks: DispAP_BBS1 (p -value = 0.047), DispAP_BBS4 (p -value = 0.011), VelMaxAP_BBS4 (p -value = 0.041), VelMinAP_BBS5 (p -value = 0.030), VelMinAP_BBS6 (p -value = 0.018), VelMaxAP_BBS6 (p -value = 0.022), DispML_BBS7 (p -value = 0.046), VelMaxML_BBS7 (p -value = 0.046), DispAP_BBS8 (p -value = 0.001), and VelMinAP_BBS14 (p -value = 0.032) and for TUG's task: VelMaxAP_Walk (p -value = 0.047). Clinical scales scores showed a decreased time to perform the TUG clinical scale, as expected. The BBS scores (before: 55.83 points, after: 55.83 points) are in accordance with those expected for healthy people (values between 41 and 56 points) [78], with the TUG scores (before: 10.67 s, after: 10.48 s) at the threshold of the same classification (less than 10 s) [79]. Sensor-based measures enable to find significant improvements during clinical test whereas no significant differences were found in the BBS and TUG scores. This shows the relevance for collecting objective metrics even when performing clinical tests.

Overall, the proposed VR-based balance training tool was able to improve stability in virtual challenges performed by healthy subjects, mainly at the walking level, with only two trials. Besides the balance results being encouraging, the tool proved to be well accepted by the users. User's experience evaluation tests proved the high acceptability of the VR-based tool by the participants, who were interested during the VR intervention, experiencing a sense of presence, involvement, and realism by the VRE created. Findings point out that the tool seems promising for the rehabilitation of static and dynamic balance as a complement to conventional physical therapy.

7. CONCLUSIONS

Stroke has a negative impact worldwide, being the leading cause of long-term disability, usually including loss of balance that limits the survivor's daily life. However, the survivors may regain their motor independence through neuroplasticity phenomenon, achieved by rehabilitation, including rehabilitation driven by robotic devices, such as VR tools. There is evidence that using VR tools as a complement to physical therapies improves and accelerates the user's recovery, as VREs can be customised to the user's imminent needs and provide intensive, repetitive, and enthusiastic training. In this sense, this dissertation designed, developed, and preliminarily validated a fully immersive VR tool, based on a user-centered design, to maximize the user's recovery, acceptability, and enthusiasm.

The state of the art on VR tools developed for post-stroke balance rehabilitation reveals that there is a lack of VR tools to be used in this field with a user-centered design. From current studies, there is a prevalence to use screens as VR technology, followed by HMD. However, there is a lack of combination of these two technologies. Cameras and balance boards are the most used sensors. The motor tasks most performed are weight shifting/bearing, treadmill walking, stepping, pelvic/hip and knee movements. Most of the VR tools comprise a closed-loop control, with virtual challenges generally aiming to catch, avoid, and navigate virtual objects, usually belonging to commercial systems with the main purpose of entertainment, with no user-centered design solutions. However, walking was mainly addressed alone, and in an open loop, in opposition to the remaining motor tasks. Thus, in this sense, there is space to create wearable VR-based tools combining walking with other motor tasks and in a closed-loop. Visual and auditory feedback are the stimuli mostly used, having a lack of vibrotactile actuators in VR tools. BBS and TUG are the most used clinical scales to assess static and dynamic balance that are the main difficulties in post-stroke patients.

The designed VR-based tool has a fully wearable design. It combines the HTC Vive Pro to immerse the user in the VRE through HMD, and the Xsens MVN Awinda, in a full-body configuration, as well as the HTC controllers to allow the user to interact with the VRE. The developed tool provides visual, sonorous, and vibrotactile stimulation through HMD, built-in headphones, and HTC controllers, respectively. In addition to the HMD, a screen was used to allow the therapist to follow, in real-time, the user's performance during balance training and, consequently, provide additional support to patients through auditory instructions.

The developed VR tool is based on the user's home ADLs and attends to the most performed motor tasks in balance training-related literature and in the BBS and TUG clinical tests. The VR tool addresses nine motor tasks such as walking, stepping, sit-to-stand and stand-to-sit, knee flexion and extension,

weight shifting, trunk and pelvic/hip movement, looking over the shoulders, standing upright on one leg, and reach with hands as far as possible. They were included in four virtual challenges, namely, Fruit Catcher, Cooking, Take a Shower, and Watch TV. The integration of first and second-person views of an avatar mimicking user's movements in real-time, grab objects, controllers' vibration, real-time COM visualization in the second-person view, turn on the Tv, shower and bathtub rim's sounds, stepping up the tree ladder, and customise the kitchen shelves' height, were the main control strategies developed to create dynamism to the static VRE, and allow the user to interact and receive real-time feedback.

A questionnaire on the ADLs most performed by people and that require balance was developed as a parallel study. The results reveal that the activities most performed and appreciated by the general population were in line with three of the four virtual challenges: Cooking, Take a Shower, and Watch Tv. Furthermore, it was observed that age influences the most appreciated ADLs, being a factor that should be considered in future research when developing virtual challenges.

The validation protocol was carried out, including six healthy and young participants with any type of balance injuries. Healthy subjects were enrolled since this preliminary validation aims to assess the user's experience and operability of the proposed VR tool, and assess the impact (either positive or negative) on motor function. All participants felt well throughout the VR sessions, that includes rest breaks, with no negative occurrences to report. Primary and secondary sensor-based outcomes were successfully measured through Xsens MVN Awinda before, during, and after VR intervention. In addition, virtual challenges scores were considered, as well the user's experience evaluation tests IMI and IPQ, aiming to assess the user's subjective experienced related to the performed activity, and the sense of presence in the VRE.

The results from the validation protocol showed statistically significant differences in COM displacement in ML direction, and minimum COM velocity in AP direction (Watch Tv, mainly at the walking level), and maximum COM velocity in AP direction (Cooking virtual challenge) between consecutive trials of the VR training. Although significantly, the latter shows a decreased velocity, which is not desired in balance training. Virtual challenges scores showed improvements for some of the participants in the number of apples caught (Fruit Catcher virtual challenge), in the number of times the user kicked the bathtub and in the time the sound played inside the bathtub (Take a Shower virtual challenge). All other virtual challenges scores presented the maximum score for all participants. Further improvements were reported, by comparing the balance function before and after VR intervention. TUG improved the clinical assessment by decreasing the time to perform the whole test, and BBS maintained the results since all participants, except one, presented the maximum score for both trials before and after VR training due to

their healthy condition. These findings reveal that this tool can be effective for balance rehabilitation, as a complement to conventional physical therapies.

The results from IMI's questionnaire proved that participants felt a higher interest and enjoyment, as well as a higher competence while performing the virtual challenges, proving the high acceptability of the tool. Moreover, participants revealed that they see value and usefulness in the tool for improving not only balance and posture, but also lower limb injuries. The IPQ questionnaire revealed that participants felt immersed in the virtual world due to the level of realism and sense of presence experienced, which is important for the best and fast improvements.

This dissertation allows to answer the RQs appointed in Chapter 1:

- **RQ1:** What specifications should be considered for the user-centered design of VR-based post-stroke balance rehabilitation?

Chapter 2 answered this RQ. VR technology, sensor integration, motor tasks, and virtual challenges, as well as the type of feedback received by the participants are the specifications that should be considered for the design on a VR tool for balance rehabilitation. There is a need for using wearable VR and sensor technologies to enable balance training during static and dynamic motor tasks. The virtual challenges should encourage the users to perform daily motor tasks, which should be selected in accordance with the user's needs in ADLs and preferences towards a user-centered design. Moreover, it is necessary to ensure that the VR enables multimodal feedback (visual, auditory, and haptic stimuli), commonly received in daily living, to allow a more realistic experience.

- **RQ2:** What factors should be considered for a user-centered design of a VR-based tool in balance training?

Chapter 4 answered this RQ. According to the participants' answers to the questionnaire about ADLs that require balance, among the assessed factors, age showed to influence the most appreciated ADLs. Thus, future research should consider age when designing virtual challenges, to create a more user-centered design VR tool, since the activities most enjoyed by people differ with aging.

- **RQ3:** Which are the effects of a fully immersive VR-based tool in balance training?

Chapter 6 answered this RQ. The primary outcomes revealed a statistically significant improvement of the minimum COM velocity in AP direction (p -value = 0.020) and in the COM

displacement in the ML direction (p -value = 0.049) in the walking motor task of the virtual challenge Watch Tv. This suggests that, from the first to the second trial, participants were able not only to walk faster but to do so with more stable balance control, decreasing their side-to-side movement directions. In addition to these metrics, many others showed considerable improvements, although not enough to be significant. The results provided by the clinical tests BBS and TUG also revealed appreciable improvements in some of the metrics assessed. Furthermore, the total time to perform the TUG decreased with only two trials of VR training (before VR training: 10.673 ± 0.525 s; after VR training: 10.480 ± 0.437 s).

7.1 Future Work

The future work comprises the following research directions: (i) to increase the number of virtual challenges, attending to the ADLs reported in the questionnaire, namely driving a car and dancing; (ii) to increase the number of motor tasks addressed per virtual challenge; (iii) to implement different levels of difficulty in each virtual challenge so that it can be used by patients with different disability levels and progressively increase the level of difficulty as they improve; (iv) to customise all virtual challenges according to user's anthropometric data; (v) to update the virtual challenges of the VR-based tool considering the age factor (vi) to carry out a more balanced study of the factors that influence the most performed and appreciated ADLs; (vii) to improve the aesthetic design of the VR tool by creating a more interactive menu with instructions and a window on the screen with the user's real time score, according to the performance in the virtual challenge; (viii) to perform a validation protocol with end-users with balance disorders (e.g., post-stroke patients, elderly people) through a randomised controlled study with a longer training by increasing the number of VR sessions. Further work involves scientific dissemination of the achieved results in peer-review ISI/Scopus journals and communications activities next to hospitals, rehabilitation clinics, and care facilities to motivate their interest to join in the end-user's validation study.

REFERENCES

- [1] "WHO EMRO | Stroke, Cerebrovascular accident | Health topics." <http://www.emro.who.int/health-topics/stroke-cerebrovascular-accident/index.html> (accessed Jan. 21, 2021).
- [2] R. Gupta, "Stroke: a leading cause of long term disability." <https://www.fortishealthcare.com/blog/stroke-leading-long-term-disability/> (accessed Oct. 31, 2021).
- [3] "Balance problems - Symptoms and causes - Mayo Clinic." <https://www.mayoclinic.org/diseases-conditions/balance-problems/symptoms-causes/syc-20350474> (accessed Oct. 30, 2021).
- [4] "Balance Disorders — Causes, Types & Treatment | NIDCD." <https://www.nidcd.nih.gov/health/balance-disorders> (accessed Oct. 30, 2021).
- [5] "Balance | Definition of Balance by Merriam-Webster." <https://www.merriam-webster.com/dictionary/balance> (accessed Oct. 31, 2021).
- [6] "Balance - Harvard Health." <https://www.health.harvard.edu/topics/balance> (accessed Oct. 31, 2021).
- [7] "Falls." <https://www.who.int/news-room/fact-sheets/detail/falls> (accessed Oct. 31, 2021).
- [8] "Basic Facts about Basic Facts | Aging & Health A-Z | American Geriatrics Society | HealthInAging.org." <https://www.healthinaging.org/a-z-topic/balance-problems/basic-facts> (accessed Oct. 31, 2021).
- [9] M. H. Kaveh, F. Bahadori, A. Doosti, and A. Asadollahi, "The effect of balance exercise training on balance status, and quality of life in elderly women: A randomized controlled trial," *Malaysian J. Med. Heal. Sci.*, vol. 17, no. 2, pp. 129–136, 2021.
- [10] Courtney E. Ackerman, "What is Neuroplasticity? A Psychologist Explains [+14 Exercises]." <https://positivepsychology.com/neuroplasticity/> (accessed Oct. 31, 2021).
- [11] U. B. Rahayu, S. Wibowo, I. Setyopranoto, and M. Hibatullah Romli, "Effectiveness of physiotherapy interventions in brain plasticity, balance and functional ability in stroke survivors: A randomized controlled trial," *NeuroRehabilitation*, vol. 47, no. 4, pp. 463–470, 2020, doi: 10.3233/NRE-203210.
- [12] C. Rossano and P. Terrier, "Visually-guided gait training in paretic patients during the first rehabilitation phase: Study protocol for a randomized controlled trial," *Trials*, vol. 17, no. 1, pp. 1–9, 2016, doi: 10.1186/s13063-016-1630-8.
- [13] S. Guo, H. Cai, and J. Guo, "A Novel Fuzzy Neural Network-based Rehabilitation Stage Classifying

- Method for the Upper Limb Rehabilitation Robotic System,” *2020 IEEE Int. Conf. Mechatronics Autom. ICMA 2020*, pp. 261–266, 2020, doi: 10.1109/ICMA49215.2020.9233519.
- [14] V. Klamroth-Marganska, “Stroke rehabilitation: Therapy robots and assistive devices,” *Adv. Exp. Med. Biol.*, vol. 1065, pp. 579–587, 2018, doi: 10.1007/978-3-319-77932-4_35.
- [15] R. Gassert and V. Dietz, “Rehabilitation robots for the treatment of sensorimotor deficits: A neurophysiological perspective,” *J. Neuroeng. Rehabil.*, vol. 15, no. 1, pp. 1–15, 2018, doi: 10.1186/s12984-018-0383-x.
- [16] T. Bao *et al.*, “Effects of long-term balance training with vibrotactile sensory augmentation among community-dwelling healthy older adults: a randomized preliminary study,” *J. Neuroeng. Rehabil.*, vol. 15, no. 1, p. 5, Dec. 2018, doi: 10.1186/s12984-017-0339-6.
- [17] G. Tieri, G. Morone, S. Paolucci, and M. Iosa, “Virtual reality in cognitive and motor rehabilitation: facts, fiction and fallacies,” *Expert Rev. Med. Devices*, vol. 15, no. 2, pp. 107–117, 2018, doi: 10.1080/17434440.2018.1425613.
- [18] F. Arcuri, C. Porcaro, I. Ciancarelli, P. Tonin, and A. Cerasa, “Electrophysiological correlates of virtual-reality applications in the rehabilitation setting: New perspectives for stroke patients,” *Electron.*, vol. 10, no. 7, 2021, doi: 10.3390/electronics10070836.
- [19] M. C. Howard, “A meta-analysis and systematic literature review of virtual reality rehabilitation programs,” *Comput. Human Behav.*, vol. 70, pp. 317–327, 2017, doi: 10.1016/j.chb.2017.01.013.
- [20] M. Francesca, “Virtual Reality Rehabilitation - The Future of Physical Therapy.” <https://imotions.com/blog/virtual-reality-rehabilitation/> (accessed Nov. 01, 2021).
- [21] A. Asadzadeh, T. Samad-Soltani, Z. Salahzadeh, and P. Rezaei-Hachesu, “Effectiveness of virtual reality-based exercise therapy in rehabilitation: A scoping review,” *Informatics Med. Unlocked*, vol. 24, p. 100562, 2021, doi: 10.1016/j.imu.2021.100562.
- [22] R. Mohammadi, A. V. Semnani, M. Mirmohammadkhani, and N. Grampurohit, “Effects of Virtual Reality Compared to Conventional Therapy on Balance Poststroke: A Systematic Review and Meta-Analysis,” *J. Stroke Cerebrovasc. Dis.*, vol. 28, no. 7, pp. 1787–1798, Jul. 2019, doi: 10.1016/j.jstrokecerebrovasdis.2019.03.054.
- [23] D. Corbetta, F. Imeri, and R. Gatti, “Rehabilitation that incorporates virtual reality is more effective than standard rehabilitation for improving walking speed, balance and mobility after stroke: a systematic review,” *J. Physiother.*, vol. 61, no. 3, pp. 117–124, Jul. 2015, doi: 10.1016/j.jphys.2015.05.017.

- [24] L. Barcala, L. A. C. Grecco, F. Colella, P. R. G. Lucareli, A. S. I. Salgado, and C. S. Oliveira, "Visual Biofeedback Balance Training Using Wii Fit after Stroke: A Randomized Controlled Trial," *J. Phys. Ther. Sci.*, vol. 25, no. 8, pp. 1027–1032, 2013, doi: 10.1589/jpts.25.1027.
- [25] K. H. Cho, K. J. Lee, and C. H. Song, "Virtual-Reality Balance Training with a Video-Game System Improves Dynamic Balance in Chronic Stroke Patients," *Tohoku J. Exp. Med.*, vol. 228, no. 1, pp. 69–74, 2012, doi: 10.1620/tjem.228.69.
- [26] K. H. Cho and W. H. Lee, "Virtual Walking Training Program Using a Real-world Video Recording for Patients with Chronic Stroke," *Am. J. Phys. Med. Rehabil.*, vol. 92, no. 5, pp. 371–384, May 2013, doi: 10.1097/PHM.0b013e31828cd5d3.
- [27] K. H. Cho and W. H. Lee, "Effect of treadmill training based real-world video recording on balance and gait in chronic stroke patients: A randomized controlled trial," *Gait Posture*, vol. 39, no. 1, pp. 523–528, Jan. 2014, doi: 10.1016/j.gaitpost.2013.09.003.
- [28] J. S. Huh, Y.-S. Lee, C.-H. Kim, Y.-S. Min, M.-G. Kang, and T.-D. Jung, "Effects of Balance Control Training on Functional Outcomes in Subacute Hemiparetic Stroke Patients," *Ann. Rehabil. Med.*, vol. 39, no. 6, p. 995, 2015, doi: 10.5535/arm.2015.39.6.995.
- [29] T. In, K. Lee, and C. Song, "Virtual Reality Reflection Therapy Improves Balance and Gait in Patients with Chronic Stroke: Randomized Controlled Trials," *Med. Sci. Monit.*, vol. 22, pp. 4046–4053, Oct. 2016, doi: 10.12659/MSM.898157.
- [30] J. H. Kim, S. H. Jang, C. S. Kim, J. H. Jung, and J. H. You, "Use of Virtual Reality to Enhance Balance and Ambulation in Chronic Stroke: A Double-Blind, Randomized Controlled Study," *Am. J. Phys. Med. Rehabil.*, vol. 88, no. 9, pp. 693–701, Sep. 2009, doi: 10.1097/PHM.0b013e3181b33350.
- [31] S. H. Lee *et al.*, "Feasibility and Effects of Newly Developed Balance Control Trainer for Mobility and Balance in Chronic Stroke Patients: A Randomized Controlled Trial," *Ann. Rehabil. Med.*, vol. 36, no. 4, p. 521, 2012, doi: 10.5535/arm.2012.36.4.521.
- [32] I.-W. Lee, Y.-N. Kim, and D.-K. Lee, "Effect of a virtual reality exercise program accompanied by cognitive tasks on the balance and gait of stroke patients," *J. Phys. Ther. Sci.*, vol. 27, no. 7, pp. 2175–2177, 2015, doi: 10.1589/jpts.27.2175.
- [33] R. Lloréns, J.-A. Gil-Gómez, M. Alcañiz, C. Colomer, and E. Noé, "Improvement in balance using a virtual reality-based stepping exercise: a randomized controlled trial involving individuals with chronic stroke," *Clin. Rehabil.*, vol. 29, no. 3, pp. 261–268, Mar. 2015, doi: 10.1177/0269215514543333.

- [34] Y.-H. Park, C. Lee, and B.-H. Lee, "Clinical usefulness of the virtual reality-based postural control training on the gait ability in patients with stroke," *J. Exerc. Rehabil.*, vol. 9, no. 5, pp. 489–494, Oct. 2013, doi: 10.12965/jer.130066.
- [35] D.-S. Park, D.-G. Lee, K. Lee, and G. Lee, "Effects of Virtual Reality Training using Xbox Kinect on Motor Function in Stroke Survivors: A Preliminary Study," *J. Stroke Cerebrovasc. Dis.*, vol. 26, no. 10, pp. 2313–2319, Oct. 2017, doi: 10.1016/j.jstrokecerebrovasdis.2017.05.019.
- [36] B. S. Rajaratnam *et al.*, "Does the Inclusion of Virtual Reality Games within Conventional Rehabilitation Enhance Balance Retraining after a Recent Episode of Stroke?," *Rehabil. Res. Pract.*, vol. 2013, pp. 1–6, 2013, doi: 10.1155/2013/649561.
- [37] Y. B. Song, M. H. Chun, W. Kim, S. J. Lee, J. H. Yi, and D. H. Park, "The Effect of Virtual Reality and Tetra-Ataxiometric Posturography Programs on Stroke Patients With Impaired Standing Balance," *Ann. Rehabil. Med.*, vol. 38, no. 2, p. 160, 2014, doi: 10.5535/arm.2014.38.2.160.
- [38] G. I. Yatar and S. A. Yildirim, "Wii Fit balance training or progressive balance training in patients with chronic stroke: a randomised controlled trial," *J. Phys. Ther. Sci.*, vol. 27, no. 4, pp. 1145–1151, 2015, doi: 10.1589/jpts.27.1145.
- [39] D. L. Jaffe, D. A. Brown, C. D. Pierson-Carey, E. L. Buckley, and H. L. Lew, "Stepping over obstacles to improve walking in individuals with poststroke hemiplegia," *J. Rehabil. Res. Dev.*, vol. 41, no. 3A, p. 283, 2004, doi: 10.1682/JRRD.2004.03.0283.
- [40] J. Jung, J. Yu, and H. Kang, "Effects of Virtual Reality Treadmill Training on Balance and Balance Self-efficacy in Stroke Patients with a History of Falling," *J. Phys. Ther. Sci.*, vol. 24, no. 11, pp. 1133–1136, 2012, doi: 10.1589/jpts.24.1133.
- [41] H.-K. Kang, Y. Kim, Y. Chung, and S. Hwang, "Effects of treadmill training with optic flow on balance and gait in individuals following stroke: randomized controlled trials," *Clin. Rehabil.*, vol. 26, no. 3, pp. 246–255, Mar. 2012, doi: 10.1177/0269215511419383.
- [42] A. Mirelman, P. Bonato, and J. E. Deutsch, "Effects of Training With a Robot-Virtual Reality System Compared With a Robot Alone on the Gait of Individuals After Stroke," *Stroke*, vol. 40, no. 1, pp. 169–174, Jan. 2009, doi: 10.1161/STROKEAHA.108.516328.
- [43] G. Morone *et al.*, "The Efficacy of Balance Training with Video Game-Based Therapy in Subacute Stroke Patients: A Randomized Controlled Trial," *Biomed Res. Int.*, vol. 2014, pp. 1–6, 2014, doi: 10.1155/2014/580861.
- [44] Y.-R. Yang, M.-P. Tsai, T.-Y. Chuang, W.-H. Sung, and R.-Y. Wang, "Virtual reality-based training improves community ambulation in individuals with stroke: A randomized controlled trial," *Gait*

- Posture*, vol. 28, no. 2, pp. 201–206, Aug. 2008, doi: 10.1016/j.gaitpost.2007.11.007.
- [45] A. Quratul *et al.*, “Comparative Analysis of Circuit Gait Training vs Virtual Reality Based Gait Training in Improving Gait among Stroke Patients,” pp. 202–206, 2021.
 - [46] Y. Xu *et al.*, “A depth camera–based, task-specific virtual reality rehabilitation game for patients with stroke: Pilot usability study,” *JMIR Serious Games*, vol. 9, no. 1, pp. 1–12, 2021, doi: 10.2196/20916.
 - [47] I. Cikajlo, M. Rudolf, R. Mainetti, and N. A. Borghese, “Multi-Exergames to Set Targets and Supplement the Intensified Conventional Balance Training in Patients With Stroke: A Randomized Pilot Trial,” *Front. Psychol.*, vol. 11, no. April, pp. 1–13, 2020, doi: 10.3389/fpsyg.2020.00572.
 - [48] P. Fishbein, Y. Hutzler, M. Ratmansky, I. Treger, and A. Dunsky, “A Preliminary Study of Dual-Task Training Using Virtual Reality: Influence on Walking and Balance in Chronic Poststroke Survivors,” *J. Stroke Cerebrovasc. Dis.*, vol. 28, no. 11, p. 104343, 2019, doi: 10.1016/j.jstrokecerebrovasdis.2019.104343.
 - [49] N. A. Mazzini, M. G. R. Almeida, J. E. Pompeu, J. C. Polese, and C. Torriani-Pasin, “A combination of multimodal physical exercises in real and virtual environments for individuals after chronic stroke: Study protocol for a randomized controlled trial,” *Trials*, vol. 20, no. 1, pp. 1–11, 2019, doi: 10.1186/s13063-019-3396-2.
 - [50] L. Sheehy *et al.*, “Home-based virtual reality training after discharge from hospital-based stroke rehabilitation: A parallel randomized feasibility trial,” *Trials*, vol. 20, no. 1, pp. 1–9, 2019, doi: 10.1186/s13063-019-3438-9.
 - [51] A. D. F. Zanona *et al.*, “Use of Virtual Rehabilitation to Improve the Symmetry of Body Temperature, Balance, and Functionality of Patients with Stroke Sequelae,” *Ann. Neurosci.*, vol. 25, no. 3, pp. 166–173, 2018, doi: 10.1159/000488581.
 - [52] J.-W. Hung, M.-Y. Yu, K.-C. Chang, H.-C. Lee, Y.-W. Hsieh, and P.-C. Chen, “Feasibility of Using Tetrax Biofeedback Video Games for Balance Training in Patients With Chronic Hemiplegic Stroke,” *PM&R*, vol. 8, no. 10, pp. 962–970, Oct. 2016, doi: 10.1016/j.pmrj.2016.02.009.
 - [53] Nintendo, “Wii Balance Board™, operations’ manual,” p. 13, 2008, [Online]. Available: <https://www.nintendo.com/consumer/downloads/wiiBalanceBoard.pdf>.
 - [54] G. Ganesh, A. Takagi, R. Osu, T. Yoshioka, M. Kawato, and E. Burdet, “Two is better than one: Physical interactions improve motor performance in humans,” *Sci. Rep.*, vol. 4, no. 1, p. 3824, May 2015, doi: 10.1038/srep03824.
 - [55] C. G. Canning, N. E. Allen, E. Nackaerts, S. S. Paul, A. Nieuwboer, and M. Gilat, “Virtual reality in

- research and rehabilitation of gait and balance in Parkinson disease,” *Nat. Rev. Neurol.*, vol. 16, no. 8, pp. 409–425, Aug. 2020, doi: 10.1038/s41582-020-0370-2.
- [56] R. Stanton, L. Ada, C. M. Dean, and E. Preston, “Biofeedback improves performance in lower limb activities more than usual therapy in people following stroke : a systematic review,” *J. Physiother.*, vol. 63, no. 1, pp. 11–16, 2017, doi: 10.1016/j.jphys.2016.11.006.
- [57] “VIVE Pro Full Kit | VIVE European Union.” <https://www.vive.com/eu/product/vive-pro-full-kit/> (accessed Jul. 28, 2021).
- [58] HTC Corporation, “VIVE Pro HMD User guide,” p. 53, 2020, [Online]. Available: https://dl4.htc.com/Web_materials/Manual/Vive_HMD/User_Guide/VIVE_Pro_HMD_User_Guide.pdf.
- [59] “ROG Strix Helios | Gaming Caixas | ROG - Republic of Gamers | ROG Portugal.” <https://rog.asus.com/pt/cases/rog-strix-helios-model/> (accessed Nov. 06, 2021).
- [60] “Família de Placas de Vídeo GeForce RTX 3080 | NVIDIA.” <https://www.nvidia.com/pt-br/geforce/graphics-cards/30-series/rtx-3080-3080ti/> (accessed Nov. 06, 2021).
- [61] “MVN Analyze.” <https://www.xsens.com/products/mvn-analyze> (accessed Jul. 31, 2021).
- [62] Xsens, “MVN User Manual,” no. March, p. 162, 2021, [Online]. Available: https://www.xsens.com/hubfs/Downloads/usermanual/MVN_User_Manual.pdf.
- [63] “MTw Awinda.” https://www.xsens.com/products/mtw-awinda?utm_term=awinda&utm_medium=ppc&utm_campaign=SEC+%7C+Search+%7C+Brand&utm_source=adwords&hsa_cam=11537759453&hsa_src=g&hsa_mt=p&hsa_ver=3&hsa_net=adwords&hsa_tgt=aud-1003050775620:kwd-1115465335414&hsa_acc=1306794700&hsa_grp=115407376991&hsa_kw=awinda&hsa_ad=476864834396&gclid=Cj0KCQjw6ZOIBhDdARIsAMf8YyGCh2Mc-1izktcTkHRDgAa90kjWZR6U5rXFF4YWZKrSRE2Kd7Vb80aAoewEALw_wcB (accessed Aug. 01, 2021).
- [64] “Physical Therapy: What to Expect, How Long it Takes, and Life After.” <https://www.ortholinc.com/article-id-fix/296-physical-therapy-what-to-expect-how-long-it-takes-and-life-after> (accessed Dec. 24, 2021).
- [65] “MVN real-time network streaming Protocol Specification,” Sep. 2018. https://www.xsens.com/hubfs/Downloads/Manuals/MVN_real-time_network_streaming_protocol_specification.pdf (accessed Aug. 06, 2021).
- [66] L. W. Chu, A. Y. Y. Chiu, and I. Chi, “Impact of falls on the balance, gait, and activities of daily

- living functioning in community-dwelling Chinese older adults,” *Journals Gerontol. - Ser. A Biol. Sci. Med. Sci.*, vol. 61, no. 4, pp. 399–404, 2006, doi: 10.1093/gerona/61.4.399.
- [67] M. E. Mlinac and M. C. Feng, “Assessment of Activities of Daily Living, Self-Care, and Independence,” *Arch. Clin. Neuropsychol.*, vol. 31, no. 6, pp. 506–516, 2016, doi: 10.1093/arclin/acw049.
- [68] “Standard Bathtub Dimensions For Every Type of Tub | Badeloft.” <https://www.badeloftusa.com/ideas/bathtub-dimensions/> (accessed Nov. 12, 2021).
- [69] “List of Standard Table & Chair Heights | How to Calculate the Ideal Height.” <https://parotas.com/en/standard-table-chair-heights-guide/> (accessed Nov. 13, 2021).
- [70] V. Lugade, V. Lin, and L. S. Chou, “Center of mass and base of support interaction during gait,” *Gait Posture*, vol. 33, no. 3, pp. 406–411, 2011, doi: 10.1016/j.gaitpost.2010.12.013.
- [71] “MVN Unity Live Plugin 2020.” https://base.xsens.com/knowledgebase/s/article/MVN-Unity-Live-Plugin-2020?language=en_US (accessed Oct. 19, 2021).
- [72] “About the VIVE controllers.” https://www.vive.com/us/support/vive/category_howto/about-the-controllers.html (accessed Oct. 20, 2021).
- [73] “Ergonomia da Cozinha - Arquidicas.” <https://www.arquidicas.com.br/ergonomia-da-cozinha/> (accessed Nov. 22, 2021).
- [74] “Pensão de velhice - seg-social.pt.” <https://www.seg-social.pt/pensao-de-velhice> (accessed Dec. 24, 2021).
- [75] P. F. Edemekong, D. L. Bomgaars, S. Sukumaran, and S. B. Levy, “Activities of Daily Living,” *Encycl. Neurol. Sci.*, pp. 47–48, Sep. 2021, doi: 10.1016/B978-0-12-385157-4.00464-4.
- [76] “igroup presence questionnaire (IPQ) overview | igroup.org – project consortium.” <http://www.igroup.org/pq/ipq/index.php> (accessed Dec. 13, 2021).
- [77] J. L. Reynolds, “Measuring intrinsic motivations,” *Handb. Res. Electron. Surv. Meas.*, no. Imi, pp. 170–173, 2006, doi: 10.4018/978-1-59140-792-8.ch018.
- [78] J. E. Pizzorno and M. T. Murray, *Textbook of Natural Medicine 5Th Edition*, vol. 1, no. 9. 2021.
- [79] “Timed Up and Go (TUG) – Strokengine.” <https://strokengine.ca/en/assessments/timed-up-and-go-tug/> (accessed Dec. 29, 2021).

APPENDIX I – PRIMARY AND SECONDARY OUTCOME MEASURES

Tables 0.1 to 0.14 present the results of the primary: COM displacement in AP and ML direction (cm), and minimum and minimum COM velocity in AP and ML direction (cm/s); and secondary outcome measures: Rom of the knee joint angle on the sagittal plane (degrees), maximum hand position to the left, forward, and right sided (cm), as well temporal (stride time [s]) and spatial (stride length [cm]) gait parameters, according to the motor tasks addressed by each of the four virtual challenges developed: Catch Fruit, Take a Shower, Cooking, and Watch Tv.

Table 0.1 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), and number of steps climbed by each participant, in both trials, while climbing stairs (CS), in Fruit Catcher virtual challenge

“Fruit Catcher” Virtual Challenge											
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes		
			COM displacement (cm)		COM velocity (cm/s)				ROM of knee joint angle (sagittal plane) (degrees)		Virtual challenge Score
			AP	ML	AP		ML		Left	Right	Number of steps climbed
					Min	Max	Min	Max			
CS	T1	P1	11.04	18.08	- 6.01	8.35	- 21.19	16.73	81.28	84.52	6
		P2	8.11	13.41	- 6.84	9.06	- 14.94	14.18	84.22	67.49	6
		P3	22.59	24.69	- 6.13	10.46	- 32.71	25.42	86.00	76.43	6
		P4	18.61	11.30	- 4.58	16.97	- 14.31	18.21	71.17	74.77	6
		P5	8.08	15.67	- 5.50	7.54	- 15.73	15.41	66.77	72.19	6
		P6	18.48	24.06	- 4.50	11.46	- 22.03	20.07	85.65	88.88	6
	T2	P1	13.28	18.60	- 4.40	7.43	- 18.29	14.32	71.33	75.77	6
		P2	10.77	12.13	- 5.79	8.05	- 15.20	12.86	80.01	67.93	6
		P3	17.88	20.88	- 4.00	11.73	- 29.35	19.68	97.25	80.19	6
		P4	12.44	9.38	- 4.11	11.24	- 15.04	21.24	75.53	68.21	6
		P5	6.96	10.56	- 5.58	10.44	- 17.09	15.09	68.87	69.49	6
		P6	13.29	24.34	- 5.30	11.49	- 25.31	18.10	82.09	86.18	6

Table 0.2 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), maximum hand position (m) for left, forward and right directions, and number of apples caught by each participant, in both trials, while catching fruits (CF), in Fruit Catcher virtual challenge

“Fruit Catcher” Virtual Challenge												
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes			
			COM displacement (cm)		COM velocity (cm/s)				Maximum hand position (cm)			Virtual challenge Score
			AP	ML	AP		ML		Left	Forward	Right	Number of apples caught
					Min	Max	Min	Max				
CF	T1	P1	21.54	12.74	- 12.16	12.03	-6.34	6.76	39.37	79.53	56.64	6
		P2	12.39	16.19	- 9.88	8.04	-11.87	10.25	58.97	84.66	68.14	5
		P3	10.76	22.37	- 13.80	10.55	-20.90	17.11	49.43	87.74	73.55	7
		P4	16.15	25.48	- 10.63	10.14	-14.67	19.28	53.50	93.93	79.29	9
		P5	11.65	14.09	- 9.55	8.02	-10.22	10.29	53.02	86.29	63.11	4
		P6	17.59	31.12	- 11.78	8.11	-21.26	22.25	55.73	84.95	78.48	9
	T2	P1	15.73	17.42	- 13.04	9.79	-11.48	7.54	41.00	78.95	60.63	6
		P2	16.03	21.19	- 10.02	5.90	-15.77	13.69	58.86	91.44	72.25	7
		P3	20.45	19.27	- 13.12	11.28	-9.75	7.90	41.81	95.57	69.33	6
		P4	14.04	28.40	- 12.63	12.36	-19.08	15.12	54.01	91.53	77.94	9
		P5	10.86	15.98	- 7.60	8.37	-7.99	8.42	51.97	78.84	58.51	4
		P6	18.98	30.42	- 15.68	8.45	-15.64	15.78	60.63	84.47	76.86	9

Table 0.3 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), and number of times each participant kicked the bathtub rim, in both trials, while entering to the bathtub (EB), in Take a Shower virtual challenge

"Take a Shower" Virtual Challenge											
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes		
			COM displacement (cm)		COM velocity (cm/s)				ROM of knee joint angle (sagittal plane) (degrees)		Virtual challenge Score
			AP	ML	AP		ML		Left	Right	Number of times the user kicked the bathtub rim
					Min	Max	Min	Max			
EB	T1	P1	101.37	35.13	- 24.71	52.64	- 39.76	35.52	110.17	108.48	21
		P2	84.01	18.07	- 10.97	55.70	- 12.58	10.15	109.56	105.69	3
		P3	85.14	16.57	- 15.29	55.49	- 29.90	24.86	106.85	112.83	5
		P4	89.23	15.61	- 6.50	50.78	- 16.19	16.04	112.77	113.84	1
		P5	92.36	26.42	- 12.65	83.71	- 24.97	29.24	109.63	90.91	0
		P6	81.20	20.48	- 7.86	31.84	-12.39	13.83	105.26	113.01	1
	T2	P1	91.70	22.83	- 16.94	43.74	- 21.82	24.90	108.92	106.91	1
		P2	79.24	15.54	- 14.05	56.42	- 10.29	18.78	114.99	108.87	1
		P3	78.99	17.70	- 9.92	70.98	- 18.59	26.11	100.10	114.15	1
		P4	94.68	29.59	-14.06	62.21	- 30.21	32.18	114.69	114.79	1
		P5	93.73	14.13	- 8.13	76.15	- 25.35	21.65	107.54	96.21	0
		P6	90.23	21.03	- 7.30	50.83	- 16.38	11.36	103.66	115.68	1

Table 0.4 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), and the amount of time the sound played (s) 10 s being the total, in both trials, while each participant is inside the bathtub (IB), in Take a Shower virtual challenge

"Take a Shower" Virtual Challenge											
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes		
			COM displacement (cm)		COM velocity (cm/s)				ROM of knee joint angle (sagittal plane) (degrees)		Virtual Challenge Score
			AP	ML	AP		ML		Left	Right	Sound playing duration inside the bathtub
					Min	Max	Min	Max			
IB	T1	P1	9.51	14.63	- 7.42	7.21	- 13.00	20.72	19.48	93.47	10.00
		P2	9.77	17.78	- 10.10	9.97	- 15.85	21.63	92.81	27.42	10.00
		P3	5.50	10.09	- 7.18	7.89	- 12.81	11.62	17.93	103.33	2.58
		P4	9.44	15.75	- 5.71	10.56	- 10.42	20.13	28.12	91.90	4.60
		P5	7.34	10.50	- 8.93	7.23	- 6.76	12.13	10.95	80.38	10.00
		P6	7.72	16.16	- 14.72	12.12	- 6.16	15.04	32.25	87.49	3.91
	T2	P1	8.61	14.52	- 8.91	11.10	- 11.79	18.35	23.95	95.67	4.53
		P2	9.94	16.58	- 6.53	9.63	- 10.37	19.52	97.22	31.33	10.00
		P3	6.75	8.42	- 7.72	5.63	- 6.64	10.20	28.16	96.73	10.00
		P4	13.88	24.00	- 8.21	9.09	- 34.66	41.48	44.15	79.74	1.74
		P5	7.76	11.37	- 5.13	8.46	- 7.79	13.09	12.02	73.14	10.00
		P6	5.65	10.94	- 4.18	6.53	- 8.52	8.48	11.15	67.21	10.00

Table 0.5 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and the number of ingredients caught, in both trials, by each participant, in Cooking virtual challenge

“Cooking” Virtual Challenge								
Trial	Participant	Primary Outcomes						Secondary Outcome
		COM displacement (cm)		COM velocity (cm/s)				Virtual Challenge Score
		AP	ML	AP		ML		Number of ingredients caught in kitchen's shelves
				Min	Max	Min	Max	
T1	P1	18.84	10.50	- 10.04	6.86	- 6.22	7.22	6
	P2	7.54	9.77	- 10.65	7.79	- 9.67	9.59	6
	P3	7.24	5.90	- 5.93	7.21	- 8.46	7.02	6
	P4	9.20	25.96	- 9.41	12.27	- 17.22	18.04	6
	P5	15.15	17.14	- 9.28	15.17	- 14.70	16.24	6
	P6	16.67	14.65	- 7.11	16.75	- 11.50	10.16	6
T2	P1	17.23	6.45	- 7.98	5.63	- 7.03	7.12	6
	P2	8.39	8.65	- 6.69	7.45	- 5.92	7.61	6
	P3	8.34	8.50	- 7.01	5.95	- 10.98	11.64	6
	P4	12.25	26.79	- 9.62	11.01	- 18.20	19.52	6
	P5	19.51	22.21	- 8.90	8.19	- 13.88	20.11	6
	P6	18.23	14.70	- 9.39	9.68	- 10.46	10.59	6

Table 0.6 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and ROM of both left and right knee joint angle on the sagittal plane (degrees) of each participant while sitting, in both trials, in Watch Tv virtual challenge

“Watch TV” Virtual Challenge										
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes	
			COM displacement (cm)		COM velocity (cm/s)				ROM of knee joint angle (sagittal plane) (degrees)	
			AP	ML	AP		ML		Left	Right
					Min	Max	Min	Max		
Stand-to-sit	T1	P1	45.54	3.96	- 27.25	1.38	- 4.52	5.37	67.53	67.93
		P2	40.67	4.16	- 42.85	1.65	- 4.00	2.25	78.32	81.95
		P3	25.06	2.23	- 16.23	0.94	- 7.12	4.29	84.59	83.58
		P4	31.52	3.51	- 19.80	1.83	- 7.93	6.43	99.30	97.14
		P5	36.89	1.65	- 24.70	3.09	- 3.89	5.10	65.61	64.22
		P6	30.80	5.35	- 18.95	1.87	- 5.78	2.56	70.85	83.16
	T2	P1	44.59	6.65	- 24.17	3.67	- 12.99	7.14	75.74	74.80
		P2	33.88	3.51	- 23.43	1.69	- 3.70	1.24	81.42	84.15
		P3	32.38	5.83	- 28.20	0.74	- 7.02	8.79	80.29	79.52
		P4	32.99	3.77	- 21.71	1.96	- 7.54	8.87	100.53	101.70
		P5	41.54	3.57	- 26.62	1.69	- 2.61	6.54	63.33	58.27
		P6	29.55	3.86	- 19.72	0.53	- 4.67	1.44	73.42	83.35

Table 0.7 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and ROM of both left and right knee joint angle on the sagittal plane (degrees) of each participant while standing, in both trials, in Watch Tv virtual challenge

"Watch TV" Virtual Challenge										
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes	
			COM displacement (cm)		COM velocity (cm/s)				ROM of knee joint angle (sagittal plane) (degrees)	
			AP	ML	AP		ML		Left	Right
					Min	Max	Min	Max		
Sit-to-stand	T1	P1	45.73	4.64	- 0.57	36.97	- 8.48	0.73	59.22	57.33
		P2	37.88	4.50	0.19	33.64	- 6.77	1.99	67.28	75.27
		P3	23.90	2.44	0.48	28.67	- 5.41	4.35	82.04	80.00
		P4	28.74	3.03	1.20	31.05	- 2.60	6.13	89.22	88.86
		P5	33.76	1.91	3.09	33.42	- 3.99	6.64	64.69	62.76
		P6	32.35	3.72	0.99	30.21	- 6.98	3.32	67.50	80.88
	T2	P1	43.12	3.99	- 0.66	38.97	- 5.78	2.34	64.83	66.42
		P2	35.53	2.25	- 3.35	46.44	- 4.37	3.78	65.67	75.74
		P3	30.20	1.71	- 0.76	34.67	- 5.16	4.86	67.19	68.80
		P4	26.86	3.70	1.80	30.68	- 3.46	9.45	89.94	90.53
		P5	39.13	1.90	1.25	47.23	- 4.69	5.59	60.95	54.55
		P6	28.86	3.59	- 2.72	28.95	- 1.15	3.58	72.72	81.32

Table 0.8 – Mean and standard deviation of COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), stride time (s), and stride length (m) of each participant while walking, in both trials, and if he turn on the television, in Watch Tv virtual challenge

“Watch TV” Virtual Challenge													
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes				
			COM displacement ($\bar{X} \pm \sigma$) (cm)		COM velocity ($\bar{X} \pm \sigma$) (cm/s)				ROM of knee joint angle (sagittal plane) ($\bar{X} \pm \sigma$) (degrees)		Temporal and spatial gait parameters ($\bar{X} \pm \sigma$)		Virtual challenge Score
			AP	ML	AP		ML		Left	Right	Stride Time (s)	Stride Length (cm)	Television state achieved
					Min	Max	Min	Max					
Walking	T1	P1	70.33 ± 3.64	6.95 ± 1.26	31.02 ± 5.06	54.93 ± 3.78	- 22.21 ± 3.06	11.87 ± 3.12	54.30 ± 2.65	53.85 ± 2.75	1.74 ± 0.12	70.98 ± 4.56	On
		P2	67.32 ± 6.69	7.88 ± 1.95	38.96 ± 6.21	57.09 ± 4.45	- 20.22 ± 4.92	19.78 ± 3.67	47.87 ± 1.91	47.50 ± 3.85	1.42 ± 0.05	67.85 ± 7.81	On
		P3	83.87 ± 2.47	12.61 ± 2.63	46.99 ± 2.82	70.44 ± 3.76	- 18.90 ± 2.75	27.82 ± 4.51	58.64 ± 1.35	58.12 ± 0.32	1.48 ± 0.08	84.94 ± 1.33	On
		P4	66.94 ± 8.11	8.30 ± 2.37	43.76 ± 6.53	67.41 ± 11.49	- 22.93 ± 1.92	16.89 ± 8.30	49.82 ± 4.81	52.91 ± 3.15	1.27 ± 0.10	66.74 ± 6.98	On
		P5	84.75 ± 9.79	11.66 ± 4.63	54.69 ± 9.66	79.56 ± 8.00	- 12.19 ± 5.64	26.36 ± 5.79	53.90 ± 1.78	51.26 ± 3.12	1.29 ± 0.05	84.28 ± 9.15	On
		P6	69.04 ± 35.44	7.28 ± 2.60	40.46 ± 5.18	59.64 ± 8.71	- 25.58 ± 2.10	7.44 ± 12.34	51.09 ± 14.59	52.38 ± 29.19	1.36 ± 0.68	66.91 ± 37.80	On

“Watch TV” Virtual Challenge													
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes				
			COM displacement $(\bar{X} \pm \sigma)$ (cm)		COM velocity $(\bar{X} \pm \sigma)$ (cm/s)				ROM of knee joint angle (sagittal plane) $(\bar{X} \pm \sigma)$ (degrees)		Temporal and spatial gait parameters $(\bar{X} \pm \sigma)$		Virtual challenge Score
			AP	ML	AP		ML		Left	Right	Stride Time (s)	Stride Length (cm)	Did the user turn on the Tv?
					Min	Max	Min	Max					
Walking	T2	P1	72.27 ± 10.35	7.63 ± 1.89	36.21 ± 3.73	63.19 ± 9.17	- 14.83 ± 3.69	14.05 ± 5.13	55.66 ± 2.38	56.86 ± 2.22	1.60 ± 0.12	80.34 ± 6.45	On
		P2	54.82 ± 22.80	6.41 ± 1.54	37.47 ± 8.89	53.43 ± 13.53	- 20.88 ± 4.33	11.70 ± 8.10	44.43 ± 8.19	38.88 ± 17.00	1.21 ± 0.43	54.07 ± 26.16	On
		P3	88.58 ± 2.66	9.94 ± 3.01	51.00 ± 7.45	79.39 ± 4.66	- 18.78 ± 3.90	26.72 ± 4.85	60.25 ± 1.25	58.36 ± 1.45	1.42 ± 0.12	89.88 ± 0.05	On
		P4	71.38 ± 10.76	6.90 ± 1.04	47.78 ± 6.25	70.54 ± 9.19	- 23.20 ± 3.13	13.86 ± 5.33	53.84 ± 3.71	53.74 ± 2.02	1.24 ± 0.05	70.60 ± 12.08	On
		P5	89.85 ± 6.79	7.78 ± 2.33	61.75 ± 5.92	85.66 ± 2.55	- 19.44 ± 5.33	22.52 ± 4.69	54.53 ± 1.81	53.45 ± 2.81	1.23 ± 0.03	88.88 ± 6.70	On
		P6	89.38 ± 6.74	6.24 ± 0.71	46.43 ± 6.46	72.00 ± 2.40	- 23.69 ± 0.37	14.36 ± 1.38	58.34 ± 0.37	68.05 ± 1.59	1.55 ± 0.04	90.07 ± 5.57	On

Table 0.9 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), and the BBS score of each participant, for BBS tasks 1,4,12, and 14, respectively, before and after VR training

BBS											
BBS Task		Participant	Primary Outcomes						Secondary Outcomes		Clinical Scale Assessment
			COM displacement (cm)		COM velocity (cm/s)				ROM of knee joint angle (degrees)		BBS Score
			AP	ML	AP		ML		Left	Right	
Min	Max	Min	Max								
Sit-to-stand	Before	P1	44.37	3.01	- 3.95	47.85	- 3.15	0.67	62.74	69.06	4
		P2	47.40	2.44	- 5.83	60.57	- 6.45	5.06	86.72	86.78	4
		P3	40.93	2.77	- 3.03	48.46	- 2.63	5.58	79.83	74.21	4
		P4	40.71	2.04	- 6.74	44.02	- 5.16	2.06	95.38	94.34	4
		P5	42.95	3.31	- 13.17	48.25	- 3.38	1.29	68.87	58.59	4
		P6	37.05	1.87	- 8.78	39.55	- 2.71	2.80	70.94	88.41	4
	After	P1	39.45	1.42	- 5.71	46.61	- 3.05	2.32	64.86	68.90	4
		P2	42.02	3.66	- 4.30	64.61	- 5.70	3.06	86.36	83.69	4
		P3	29.34	3.92	- 2.78	34.10	- 1.61	7.68	82.96	85.87	4
		P4	42.19	2.46	- 29.56	5.36	- 4.40	3.26	94.47	95.81	4
		P5	41.06	2.28	- 9.70	47.59	- 4.65	4.77	64.72	59.18	4
		P6	31.23	1.56	- 7.96	35.00	- 1.73	3.09	80.68	89.16	4
Stand-to-sit	Before	P1	42.92	0.54	- 38.65	3.68	- 7.93	1.60	61.41	69.42	4
		P2	44.46	4.63	- 56.28	2.33	- 4.78	1.93	80.41	81.38	4
		P3	36.53	7.15	- 43.76	0.99	- 11.58	2.50	79.01	76.08	4
		P4	42.66	3.04	- 37.03	1.38	- 2.48	1.63	95.26	94.54	4
		P5	41.08	3.48	- 35.67	3.50	- 3.48	2.20	68.02	60.54	4
		P6	32.70	4.86	- 25.74	2.95	- 1.29	3.98	70.04	86.69	4
	After	P1	40.98	1.22	- 49.18	4.05	- 2.21	2.34	62.96	65.11	4
		P2	39.78	1.64	- 49.38	3.70	- 2.70	3.86	83.53	80.65	4
		P3	29.49	5.43	-36.63	1.42	- 9.42	2.16	84.66	87.31	4
		P4	35.01	2.75	- 24.15	3.57	- 5.12	1.94	96.59	94.68	4
		P5	39.29	2.63	- 42.02	6.19	- 3.83	2.68	65.59	63.89	4
		P6	30.31	4.73	- 27.99	3.05	- 3.84	1.50	79.57	89.33	4

BBS											
BBS Task		Participant	Primary Outcomes						Secondary Outcomes		Clinical Scale Assessment
			COM displacement (cm)		COM velocity (cm/s)				ROM of knee joint angle (degrees)		BBS Score
			AP	ML	AP		ML		Left	Right	
					Min	Max	Min	Max			
Place alternate foot on step	Before	P1	6.10	18.88	- 7.32	9.52	- 27.81	25.65	67.32	70.33	4
		P2	6.10	14.42	- 8.23	10.48	- 18.58	18.25	67.58	59.61	4
		P3	5.23	16.52	- 6.66	5.76	- 18.87	19.27	83.30	77.83	4
		P4	7.10	18.23	- 9.11	11.19	- 18.93	20.90	77.09	76.02	4
		P5	9.09	14.79	- 8.21	11.24	- 19.67	20.12	67.88	60.30	4
		P6	7.00	15.03	- 8.69	10.03	- 14.79	16.61	68.37	76.38	4
	After	P1	6.74	15.05	- 6.39	7.14	- 21.33	19.53	68.72	73.23	4
		P2	5.44	15.70	- 7.87	9.45	- 20.61	22.77	65.29	62.09	4
		P3	10.95	15.99	- 6.69	6.43	- 20.44	21.45	93.70	92.96	4
		P4	8.68	15.46	- 10.34	12.38	- 18.29	18.81	74.14	78.41	4
		P5	6.15	15.72	- 5.84	8.93	- 17.03	19.37	72.32	64.58	4
		P6	6.45	15.62	- 7.23	10.78	- 16.82	17.53	77.89	83.07	4
Standing on one leg	Before	P1	6.02	13.46	- 2.80	4.93	- 18.38	1.82	89.94	7.38	4
		P2	6.82	13.38	- 6.16	6.60	- 15.20	16.37	96.06	19.18	4
		P3	2.76	9.40	- 1.56	2.70	- 11.21	1.58	92.42	4.83	4
		P4	2.61	2.30	- 4.59	13.95	- 6.34	14.16	3.84	49.73	4
		P5	3.83	9.91	- 4.78	3.34	- 3.44	11.89	3.77	69.53	4
		P6	5.01	7.75	- 3.23	6.20	- 1.27	11.30	5.79	80.50	4
	After	P1	8.79	12.37	- 2.06	9.02	- 13.96	6.73	91.58	8.15	4
		P2	4.24	11.04	- 3.77	9.57	- 17.50	2.90	83.49	9.91	4
		P3	4.77	7.16	- 0.98	4.06	- 11.80	1.75	104.84	2.99	4
		P4	3.66	6.87	- 3.04	6.15	- 3.28	8.62	17.58	86.75	4
		P5	3.37	10.81	- 4.10	8.17	- 2.11	15.06	6.48	73.06	4
		P6	4.94	6.25	- 3.17	5.06	- 2.15	9.44	8.55	79.13	4

Table 0.10 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), maximum hand forward position (cm), and the BBS score of each participant, for BBS task 8, before and after VR training

BBS										
BBS Task		Participant	Primary Outcomes						Secondary Outcomes	Clinical Scale Assessment
			COM displacement (cm)		COM velocity (cm/s)				Maximum hand position (cm)	BBS Score
			AP	ML	AP		ML		Forward	
Min	Max	Min			Max					
Reaching forward	Before	P1	11.91	1.20	- 12.52	11.04	- 1.32	1.36	62.69	4
		P2	8.14	5.07	- 9.74	8.65	- 2.63	5.14	72.40	4
		P3	10.63	3.15	- 14.25	8.56	- 3.84	4.17	59.57	4
		P4	5.99	4.04	- 7.92	3.81	- 2.97	5.41	68.19	4
		P5	10.04	2.64	- 12.86	5.05	- 2.92	3.72	67.75	4
		P6	11.93	3.10	- 12.58	5.35	- 2.94	3.32	75.29	4
	After	P1	10.26	4.83	- 15.27	10.74	- 3.30	7.48	64.52	4
		P2	6.27	3.87	- 6.52	7.82	- 3.37	3.67	68.73	4
		P3	8.97	1.40	- 8.58	9.95	- 6.35	1.18	57.56	4
		P4	5.21	2.58	- 6.74	4.19	- 2.87	3.79	66.44	4
		P5	8.31	3.20	- 6.38	6.22	- 2.20	2.23	69.22	4
		P6	11.17	3.19	- 9.73	9.22	- 1.93	4.11	75.87	4

Table 0.11 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and the BBS score of each participant, for the fourteen BBS tasks 2, 3, 5, 6, 7, 9, 10, 11, 13, respectively, before and after VR training

BBS									
BBS Task		Participant	Primary Outcomes						Clinical Scale Assessment
			COM displacement (cm)		COM velocity (cm/s)				BBS Score
					AP		ML		
							Min	Max	
Standing	Before	P1	3.62	0.98	- 1.93	1.73	- 0.41	0.52	4
		P2	2.38	0.89	- 0.85	1.01	- 0.47	0.73	4
		P3	2.17	1.22	- 1.07	0.77	- 0.65	1.32	4
		P4	1.78	0.73	- 1.15	1.37	- 0.61	0.52	4
		P5	1.50	0.37	- 4.98	0.96	- 3.53	0.44	4
		P6	1.75	0.74	- 1.96	0.81	- 0.67	0.70	4
	After	P1	4.85	0.87	- 2.14	2.33	- 0.71	0.82	4
		P2	1.98	0.78	- 0.66	0.62	- 0.48	0.48	4
		P3	1.45	0.71	- 0.90	0.86	- 0.66	0.61	4
		P4	1.68	0.93	- 2.64	0.77	- 3.64	0.53	4
		P5	1.97	0.74	- 5.39	1.27	- 2.36	0.62	4
		P6	2.24	1.44	- 1.49	0.97	- 0.79	0.79	4
Sitting	Before	P1	3.64	2.71	- 0.61	0.74	- 2.64	0.83	4
		P2	0.97	0.98	- 1.80	0.41	- 0.39	0.29	4
		P3	1.15	0.68	- 3.73	0.50	- 3.94	0.54	4
		P4	1.26	0.73	- 7.52	12.98	- 4.05	0.89	4
		P5	1.62	1.31	- 10.62	11.44	- 4.69	0.78	4
		P6	1.24	0.30	- 8.80	12.18	- 3.29	4.49	4
	After	P1	1.57	0.51	- 2.09	0.66	- 2.89	0.38	4
		P2	0.93	0.56	- 1.75	0.20	- 0.61	0.82	4
		P3	1.48	0.53	- 2.51	0.97	- 1.92	0.60	4
		P4	1.21	0.96	- 7.01	9.18	- 3.46	1.99	4
		P5	1.68	1.38	- 9.67	9.91	- 3.54	4.97	4
		P6	1.42	0.29	- 7.78	20.36	- 1.02	5.25	4

BBS									
BBS Task		Participant	Primary Outcomes						Clinical Scale Assessment
			COM displacement		COM velocity				BBS Score
			(cm)		(cm/s)				
			AP	ML	AP		ML		
				Min	Max	Min	Max		
Transfers	Before	P1	96.39	10.11	- 39.20	35.29	- 18.54	20.67	4
		P2	87.86	10.22	- 47.89	50.34	- 17.38	18.40	4
		P3	88.29	19.74	- 32.78	41.23	- 14.50	19.82	4
		P4	92.99	10.80	- 37.63	45.04	- 20.25	19.75	4
		P5	106.76	14.92	- 42.64	54.42	- 16.03	17.49	4
		P6	103.20	16.13	- 32.18	35.10	- 17.13	20.15	4
	After	P1	90.27	12.94	- 37.23	43.23	- 20.64	26.04	4
		P2	87.94	10.45	- 52.45	64.03	- 15.04	15.85	4
		P3	87.19	14.59	- 37.40	33.43	- 16.84	25.51	4
		P4	101.83	15.36	- 40.63	48.44	- 25.16	14.74	4
		P5	113.22	9.30	- 47.43	52.81	- 18.18	12.55	4
		P6	91.95	13.46	- 36.46	35.11	- 22.91	15.09	4
Standing with eyes closed	Before	P1	2.40	0.47	- 1.43	1.22	- 0.37	0.40	4
		P2	1.18	0.31	- 0.89	0.61	- 0.30	0.40	4
		P3	0.65	0.37	- 0.67	0.50	- 0.29	0.32	4
		P4	1.16	0.52	- 1.79	1.24	- 0.96	0.82	4
		P5	1.71	0.45	- 4.73	1.60	- 4.01	0.60	4
		P6	1.24	0.96	- 2.59	1.37	- 1.21	0.80	4
	After	P1	1.53	0.69	- 1.38	1.66	- 0.45	0.54	4
		P2	0.84	0.34	- 0.46	0.81	- 0.42	0.35	4
		P3	1.37	1.05	- 0.51	0.63	- 0.61	0.58	4
		P4	1.27	0.39	- 1.00	1.35	- 2.04	1.08	4
		P5	2.37	0.45	- 4.17	1.73	- 0.76	0.31	4
		P6	1.23	1.19	- 2.29	1.44	- 1.15	1.18	4

BBS									
BBS Task		Participant	Primary Outcomes						Clinical Scale Assessment
			COM displacement		COM velocity				BBS Score
			(cm)		(cm/s)				
			AP	ML	AP		ML		
				Min	Max	Min	Max		
Standing with feet together	Before	P1	2.80	1.72	- 1.62	1.52	- 0.85	1.17	4
		P2	3.10	1.02	- 0.76	0.76	- 0.76	0.59	4
		P3	0.96	1.25	- 0.81	0.81	- 0.68	0.91	4
		P4	1.97	1.30	- 1.31	0.72	- 1.53	1.86	4
		P5	1.76	1.32	- 5.49	1.64	- 1.72	1.30	4
		P6	1.47	1.27	- 2.61	1.11	- 0.99	1.03	4
	After	P1	4.51	2.26	- 2.71	1.67	- 1.60	1.36	4
		P2	2.51	1.53	- 0.67	0.86	- 0.66	1.06	4
		P3	0.99	1.33	- 0.57	0.76	- 0.67	0.83	4
		P4	1.82	1.54	- 3.94	1.03	- 2.12	4.30	4
		P5	1.73	1.28	- 3.64	1.07	- 1.02	1.60	4
		P6	2.09	1.45	- 3.97	1.58	- 1.05	1.60	4
Pick up object from the floor	Before	P1	5.01	4.03	- 7.19	4.14	- 3.24	6.24	4
		P2	6.26	2.68	- 6.81	8.94	- 4.66	4.63	4
		P3	5.58	2.31	- 9.74	5.65	- 2.98	2.77	3
		P4	10.78	8.47	- 10.49	7.05	- 6.86	7.16	4
		P5	4.58	2.83	- 6.84	9.02	- 4.37	2.42	4
		P6	7.39	2.25	- 4.54	7.28	- 2.23	2.22	4
	After VR training	P1	4.83	1.93	- 3.73	3.90	- 2.72	3.64	4
		P2	5.82	1.89	- 12.39	12.83	- 3.45	4.75	4
		P3	2.12	2.66	- 3.40	4.99	- 4.12	4.30	3
		P4	7.49	8.55	- 7.21	6.09	- 8.05	7.83	4
		P5	5.40	3.98	- 6.48	6.80	- 3.77	5.82	4
		P6	7.70	1.27	- 6.17	7.09	- 1.89	2.44	4

BBS									
BBS Task		Participant	Primary Outcomes						Clinical Scale Assessment
			COM displacement (cm)		COM velocity (cm/s)				BBS Score
					AP		ML		
			AP	ML	Min	Max	Min	Max	
Look over the shoulders	Before	P1	3.49	3.67	- 1.99	3.60	- 4.46	3.91	4
		P2	3.08	2.18	- 2.17	2.44	- 3.96	1.96	4
		P3	4.24	2.87	- 3.05	2.99	- 2.64	2.77	4
		P4	2.60	1.70	- 3.12	2.62	- 2.22	1.30	4
		P5	5.56	1.98	- 6.40	5.42	- 2.41	2.61	4
		P6	3.09	1.61	- 2.47	2.18	- 2.42	2.20	4
	After	P1	3.54	3.37	- 4.52	3.41	- 3.49	5.67	4
		P2	3.00	1.61	- 2.38	2.49	- 1.93	2.81	4
		P3	3.95	2.36	- 3.08	3.46	- 2.89	2.60	4
		P4	3.72	2.35	- 3.23	5.11	- 2.38	5.45	4
		P5	4.58	4.24	- 6.02	5.66	- 4.49	3.20	4
		P6	3.51	3.54	- 3.13	2.55	- 3.61	4.49	4
Turn 360 degrees	Before	P1	10.91	26.81	- 17.93	15.61	- 24.87	39.60	4
		P2	23.98	20.89	- 36.78	37.15	- 31.12	22.66	4
		P3	17.29	23.28	- 21.54	27.03	- 33.54	38.77	4
		P4	20.67	19.02	- 29.86	24.34	- 20.34	24.44	4
		P5	26.17	18.14	- 39.20	31.14	- 20.30	34.93	4
		P6	29.33	27.49	- 20.88	20.85	- 25.64	32.47	4
	After	P1	21.78	21.46	- 28.07	21.25	- 21.68	26.84	4
		P2	9.67	16.54	- 19.58	17.54	- 22.88	21.14	4
		P3	23.70	18.51	- 33.50	24.23	- 20.02	23.03	4
		P4	17.09	19.44	- 30.09	25.09	- 24.24	30.12	4
		P5	25.15	28.43	- 39.39	28.34	- 27.77	29.62	4
		P6	25.23	25.19	- 24.83	22.34	- 17.44	22.02	4

BBS									
BBS Task		Participant	Primary Outcomes						Clinical Scale Assessment
			COM displacement (cm)		COM velocity (cm/s)				BBS Score
			AP	ML	AP		ML		
					Min	Max	Min	Max	
Standing with one foot in front	Before	P1	1.04	2.61	- 1.25	1.15	- 1.57	2.00	4
		P2	3.17	2.79	- 1.56	1.39	- 1.86	2.09	4
		P3	1.15	1.35	- 1.00	0.72	- 1.20	1.17	4
		P4	1.83	2.71	- 1.59	1.94	- 1.22	2.07	4
		P5	1.06	1.16	- 5.11	0.84	- 1.14	2.86	4
		P6	1.53	1.04	- 1.80	4.34	- 1.52	1.14	4
	After	P1	1.83	1.84	- 1.47	0.94	- 1.13	1.19	4
		P2	1.71	1.92	- 1.07	1.72	- 3.06	2.30	4
		P3	1.51	1.94	- 0.80	1.28	- 1.20	1.11	4
		P4	1.15	2.01	- 2.47	5.89	- 1.62	6.00	4
		P5	1.84	1.41	- 4.43	1.63	- 1.74	2.61	4
		P6	2.43	1.56	- 3.81	1.38	- 1.25	2.00	4

Table 0.12 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and ROM of both left and right knee joint angle on the sagittal plane (degrees) of each participant while performing the standing TUG task, in both trials, before and after VR training

TUG										
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes	
			COM displacement (cm)		COM velocity (cm/s)				ROM of knee joint angle (sagittal plane) (degrees)	
			AP	ML	AP		ML		Left	Right
					Min	Max	Min	Max		
Sit-to-stand	Before	P1	40.44	6.30	- 0.90	43.31	- 3.63	22.26	53.97	63.60
		P2	51.36	4.25	- 3.54	64.66	- 8.49	7.18	74.07	80.43
		P3	30.92	5.70	- 0.93	42.15	- 5.16	12.77	55.97	51.21
		P4	32.65	6.68	- 7.22	40.72	- 2.80	16.44	75.27	67.54
		P5	42.09	6.21	- 11.47	62.29	- 15.53	1.27	34.13	37.80
		P6	36.11	2.10	- 7.27	47.98	- 5.58	1.74	39.86	53.23
	After	P1	40.90	3.34	- 3.20	47.73	- 3.14	13.37	60.02	59.76
		P2	47.97	8.08	- 2.29	63.47	- 11.28	0.19	60.27	78.68
		P3	26.80	6.31	- 1.43	35.34	- 2.46	10.23	64.85	66.64
		P4	40.44	6.38	- 11.34	47.19	- 28.27	11.67	60.84	56.71
		P5	37.20	4.61	- 8.90	47.89	- 2.77	15.55	53.84	47.30
		P6	30.55	2.64	- 8.96	41.03	- 3.92	5.44	65.09	74.55

Table 0.13 - Mean and standard deviation of COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), ROM of both left and right knee joint angle on the sagittal plane (degrees), stride time (s), and stride length (m) of each participant while performing the TUG walking task, before and after VR training

TUG												
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes			
			COM displacement ($\bar{X} \pm \sigma$) (cm)		COM velocity ($\bar{X} \pm \sigma$) (cm/s)				ROM of knee joint angle (sagittal plane) ($\bar{X} \pm \sigma$) (degrees)		Temporal and spatial gait parameters ($\bar{X} \pm \sigma$)	
			AP	ML	AP		ML		Left	Right	Stride Time (s)	Stride Length (cm)
					Min	Max	Min	Max				
Walking	Before	P1	118.52 ± 8.17	16.20 ± 6.82	91.69 ± 4.12	120.27 ± 3.54	- 14.75 ± 23.75	17.68 ± 20.92	61.83 ± 0.92	69.32 ± 0.67	1.16 ± 0.04	118.61 ± 3.40
		P2	106.03 ± 13.99	15.48 ± 7.02	78.86 ± 23.31	120.13 ± 12.25	- 24.42 ± 31.19	17.54 ± 18.66	62.45 ± 1.14	57.97 ± 4.00	1.09 ± 0.03	103.62 ± 24.11
		P3	114.51 ± 7.54	25.89 ± 16.75	73.99 ± 5.15	107.28 ± 3.18	- 3.27 ± 11.96	38.51 ± 19.25	66.09 ± 2.53	60.56 ± 1.64	1.32 ± 0.04	114.48 ± 6.84
		P4	123.77 ± 2.29	13.22 ± 6.30	89.37 ± 5.32	121.90 ± 4.96	- 18.75 ± 18.30	5.50 ± 17.58	62.55 ± 3.22	62.93 ± 1.11	1.21 ± 0.04	125.02 ± 3.84
		P5	118.44 ± 17.36	10.70 ± 9.58	96.77 ± 9.93	131.69 ± 5.43	- 23.87 ± 5.29	14.22 ± 16.17	58.93 ± 2.81	53.36 ± 5.56	1.05 ± 0.09	115.89 ± 24.26
		P6	110.32 ± 15.31	10.49 ± 5.55	84.75 ± 14.39	119.91 ± 4.96	- 25.66 ± 14.91	13.20 ± 12.91	61.75 ± 2.17	72.22 ± 2.07	1.11 ± 0.04	111.32 ± 18.37

TUG												
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes			
			COM displacement $(\bar{X} \pm \sigma)$ (cm)		COM velocity $(\bar{X} \pm \sigma)$ (cm/s)				ROM of knee joint angle (sagittal plane) $(\bar{X} \pm \sigma)$ (degrees)		Temporal and spatial gait parameters $(\bar{X} \pm \sigma)$	
			AP	ML	AP		ML		Left	Right	Stride Time (s)	Stride Length (cm)
					Min	Max	Min	Max				
Walking	After	P1	118.63 $\pm$ 5.36	9.27 $\pm$ 4.47	90.43 $\pm$ 1.15	123.42 $\pm$ 3.63	- 20.19 $\pm$ 14.86	7.93 $\pm$ 7.07	65.26 $\pm$ 1.09	68.10 $\pm$ 0.88	1.15 $\pm$ 0.03	121.95 $\pm$ 3.31
		P2	106.61 $\pm$ 8.17	21.34 $\pm$ 13.63	81.32 $\pm$ 10.93	106.05 $\pm$ 6.61	- 39.24 $\pm$ 26.78	4.03 $\pm$ 19.08	58.12 $\pm$ 1.83	58.71 $\pm$ 0.79	1.16 $\pm$ 0.02	109.07 $\pm$ 6.48
		P3	112.30 $\pm$ 1.86	19.31 $\pm$ 8.32	70.76 $\pm$ 2.67	103.13 $\pm$ 1.03	- 9.83 $\pm$ 7.42	26.56 $\pm$ 21.81	61.73 $\pm$ 1.62	62.53 $\pm$ 2.75	1.37 $\pm$ 0.02	112.84 $\pm$ 3.94
		P4	116.27 $\pm$ 14.85	20.19 $\pm$ 14.70	85.96 $\pm$ 12.34	115.50 $\pm$ 18.57	- 32.70 $\pm$ 16.69	- 4.51 $\pm$ 21.43	59.67 $\pm$ 2.50	59.86 $\pm$ 1.08	1.19 $\pm$ 0.06	118.46 $\pm$ 17.50
		P5	118.96 $\pm$ 7.01	11.31 $\pm$ 6.36	97.20 $\pm$ 8.74	126.01 $\pm$ 6.49	- 19.88 $\pm$ 9.28	19.21 $\pm$ 11.45	59.67 $\pm$ 1.98	56.17 $\pm$ 3.47	1.09 $\pm$ 0.02	120.92 $\pm$ 10.37
		P6	110.03 $\pm$ 5.02	10.20 $\pm$ 5.86	79.73 $\pm$ 4.84	108.32 $\pm$ 0.78	- 15.55 $\pm$ 10.96	16.41 $\pm$ 13.15	63.08 $\pm$ 2.91	72.21 $\pm$ 0.91	1.19 $\pm$ 0.01	112.12 $\pm$ 7.12

Table 0.14 - COM displacement on AP and ML directions (cm), maximum and minimum COM velocity on AP and ML directions (cm/s), and ROM of both left and right knee joint angle on the sagittal plane (degrees) of each participant while performing the TUG sitting task, before and after VR training

TUG										
Task	Trial	Participant	Primary Outcomes						Secondary Outcomes	
			COM displacement (cm)		COM velocity (cm/s)				ROM of knee joint angle (sagittal plane) (degrees)	
			AP	ML	AP		ML		Left	Right
					Min	Max	Min	Max		
Stand-to-sit	Before	P1	29.86	1.12	- 32.77	1.95	- 3.87	2.71	41.52	43.92
		P2	39.29	5.65	- 40.79	1.72	- 3.07	16.15	80.54	83.87
		P3	26.17	8.90	- 34.34	0.87	- 9.86	0.73	65.92	66.27
		P4	35.81	7.16	- 33.33	2.58	- 27.68	8.69	72.05	71.29
		P5	41.31	3.04	- 45.06	2.43	- 12.19	2.69	47.42	37.48
		P6	35.58	4.70	- 25.68	1.33	- 10.15	2.15	66.19	69.82
	After	P1	33.10	3.75	- 30.22	3.03	- 8.18	5.02	59.94	53.09
		P2	42.86	5.91	- 44.55	0.82	- 18.21	4.80	80.11	77.48
		P3	27.86	6.77	- 34.94	0.87	- 11.17	1.10	64.50	66.55
		P4	32.81	3.19	- 34.52	1.27	- 3.44	13.76	62.59	55.39
		P5	47.92	6.95	- 46.73	2.17	- 15.30	6.22	64.61	61.32
		P6	33.70	9.21	- 29.64	1.57	- 15.83	1.31	76.20	83.19

APPENDIX II – NORMALITY AND HOMOGENEITY STATISTICAL TESTS

Tables 0.15 to 0.18, 0.19 and 0.20, and 0.21 present the p-values from the normality tests (Kolmogorov-Smirnov) for the primary outcome measures: COM displacement (Disp), maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for the four virtual challenges, the sensor-based assessment of the two clinical tests (BBS and TUG), and for the BSB and TUG clinical assessment scores, respectively. In the same order, for the metrics following a normal distribution, Tables 0.22 to 0.25, 0.26 and 0.27, and 0.28, present their p-values after the homogeneity test (Levene).

Table 0.15 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for CS, and CF motor tasks of the virtual challenge “Fruit Catcher”, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Tests of Normality		
Catch Fruit	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	T1	T2
Climbing Stairs		
DispAP_CS	.200*	.200*
DispML_CS	.200*	.200*
VelMinAP_CS	.200*	.200*
VelMaxAP_CS	.200*	.200*
VelMinML_CS	.200*	.143
VelMaxML_CS	.200*	.200*
Catching Fruits		
DispAP_CF	.200*	.200*
DispML_CF	.200*	.200*
VelMinAP_CF	.200*	.200*
VelMaxAP_CF	.119	.200*
VelMinML_CF	.200*	.200*
VelMaxML_CF	.200*	.150
*. This is a lower bound of the true significance.		
a. Lilliefors Significance Correction		

Table 0.16 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for EB, and standing on one leg inside the bathtub (IB) motor tasks of the virtual challenge “Take a Shower”, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Tests of Normality		
Take a Shower	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	T1	T2
Entering in the bathtub		
DispAP_EB	.200*	.141
DispML_EB	.200*	.200*
VelMinAP_EB	.200*	.200*
VelMaxAP_EB	.059	.200*
VelMinML_EB	.200*	.200*
VelMaxML_EB	.200*	.200*
Standing on one leg		
DispAP_IB	.200*	.200*
DispML_IB	.200*	.200*
VelMinAP_IB	.200*	.200*
VelMaxAP_IB	.200*	.200*
VelMinML_IB	.200*	.005
VelMaxML_IB	.200*	.097
*. This is a lower bound of the true significance.		
a. Lilliefors Significance Correction		

Table 0.17 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, collecting food from the kitchen shelves of the virtual challenge “Cooking”, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Tests of Normality		
Cooking	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	T1	T2
Pick up the food		
DispAP_Cook	.200*	.200*
DispML_Cook	.200*	.200*
VelMinAP_Cook	.142	.200*
VelMaxAP_Cook	.191	.200*
VelMinML_Cook	.200*	.200*
VelMaxML_Cook	.197	.200*
*. This is a lower bound of the true significance. a. Lilliefors Significance Correction		

Table 0.18 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for stand-to-sit, sit-to-stand, and walking motor tasks of the virtual challenge “Watch Tv”, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Tests of Normality		
Watch TV	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	T1	T2
Stand-to-sit		
DispAP_Sit	.200*	.109
DispML_Sit	.200*	.016
VelMinAP_Sit	.200*	.200*
VelMaxAP_Sit	.122	.200*
VelMinML_Sit	.200*	.200*
VelMaxML_Sit	.200*	.200*
Sit-to-stand		
DispAP_Stand	.200*	.200*
DispML_Stand	.200*	.200*
VelMinAP_Stand	.200*	.200*
VelMaxAP_Stand	.200*	.200*
VelMinML_Stand	.200*	.200*
VelMaxML_Stand	.200*	.200*
Walking		
DispAP_Walk	.047	.157
DispML_Walk	.101	.200*
VelMinAP_Walk	.200*	.200*
VelMaxAP_Walk	.200*	.200*
VelMinML_Walk	.200*	.200*
VelMaxML_Walk	.200*	.021
*. This is a lower bound of the true significance.		
a.Lilliefors Significance Correction		

Table 0.19 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for BBS motor tasks, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Tests of Normality		
BBS	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	Pre	Post
Sit-to-stand		
DispAP_BBS1	.200*	.108
DispML_BBS1	.200*	.200*
VelMinAP_BBS1	.200*	.024
VelMaxAP_BBS1	.066	.200*
VelMinML_BBS1	.094	.200*
VelMaxML_BBS1	.200*	.055
Standing unsupported		
DispAP_BBS2	.200*	.009
DispML_BBS2	.200*	.082
VelMinAP_BBS2	.028	.200*
VelMaxAP_BBS2	.191	.188
VelMinML_BBS2	.000	.014
VelMaxML_BBS2	.092	.200*
Sitting unsupported		
DispAP_BBS3	.025	.200*
DispML_BBS3	.200*	.074
VelMinAP_BBS3	.200*	.162
VelMaxAP_BBS3	.072	.188
VelMinML_BBS3	.200*	.200*
VelMaxML_BBS3	.001	.200*
*. This is a lower bound of the true significance.		
a. Lilliefors Significance Correction		

Tests of Normality		
BBS	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	Pre	Post
Stand-to-sit		
DispAP_BBS4	.200*	.200*
DispML_BBS4	.200*	.200*
VelMinAP_BBS4	.200*	.200*
VelMaxAP_BBS4	.200*	.200*
VelMinML_BBS4	.200*	.198
VelMaxML_BBS4	.200*	.200*
Transfers		
DispAP_BBS5	.200*	.101
DispML_BBS5	.200*	.200*
VelMinAP_BBS5	.200*	.200*
VelMaxAP_BBS5	.200*	.200*
VelMinML_BBS5	.200*	.200*
VelMaxML_BBS5	.130	.043
Standing with eyes closed		
DispAP_BBS6	.200*	.200*
DispML_BBS6	.052	.200*
VelMinAP_BBS6	.200*	.200*
VelMaxAP_BBS6	.143	.200*
VelMinML_BBS6	.043	.200*
VelMaxML_BBS6	.200*	.200*
*. This is a lower bound of the true significance.		
a. Lilliefors Significance Correction		

Tests of Normality		
BBS	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	Pre	Post
Standing with feet together		
DispAP_BBS7	.200*	.200*
DispML_BBS7	.052	.014
VelMinAP_BBS7	.187	.200*
VelMaxAP_BBS7	.200*	.200*
VelMinML_BBS7	.200*	.200*
VelMaxML_BBS7	.200*	.004
Reaching forward		
DispAP_BBS8	.200*	.200*
DispML_BBS8	.200*	.200*
VelMinAP_BBS8	.069	.200*
VelMaxAP_BBS8	.200*	.200*
VelMinML_BBS8	.200*	.047
VelMaxML_BBS8	.200*	.200*
Pick up an object		
DispAP_BBS9	.200*	.200*
DispML_BBS9	.058	.188
VelMinAP_BBS9	.200*	.200*
VelMaxAP_BBS9	.200*	.063
VelMinML_BBS9	.200*	.072
VelMaxML_BBS9	.200*	.200*
*. This is a lower bound of the true significance. a. Lilliefors Significance Correction		

Tests of Normality		
BBS	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	Pre	Post
Looking over shoulders		
DispAP_BBS10	.200*	.200*
DispML_BBS10	.200*	.200*
VelMinAP_BBS10	.019	.067
VelMaxAP_BBS10	.200*	.200*
VelMinML_BBS10	.051	.200*
VelMaxML_BBS10	.200*	.200*
Turn 360 degrees		
DispAP_BBS11	.200*	.200*
DispML_BBS11	.200*	.200*
VelMinAP_BBS11	.200*	.200*
VelMaxAP_BBS11	.200*	.200*
VelMinML_BBS11	.200*	.200*
VelMaxML_BBS11	.200*	.200*
Place alternate foot on step		
DispAP_BBS12	.200*	.116
DispML_BBS12	.200*	.200*
VelMinAP_BBS12	.200*	.200*
VelMaxAP_BBS12	.105	.200*
VelMinML_BBS12	.026	.200*
VelMaxML_BBS12	.200*	.200*
*. This is a lower bound of the true significance.		
a. Lilliefors Significance Correction		

Tests of Normality		
BBS	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	Pre	Post
Standing with one foot in front		
DispAP_BBS13	.200*	.200*
DispML_BBS13	.136	.200*
VelMinAP_BBS13	.003	.200*
VelMaxAP_BBS13	.189	.001
VelMinML_BBS13	.200*	.117
VelMaxML_BBS13	.200*	.060
Standing on one leg		
DispAP_BBS14	.200*	.031
DispML_BBS14	.200*	.200*
VelMinAP_BBS14	.200*	.200*
VelMaxAP_BBS14	.091	.200*
VelMinML_BBS14	.200*	.164
VelMaxML_BBS14	.164	.200*
*. This is a lower bound of the true significance. a. Lilliefors Significance Correction		

Table 0.20 - The p-values of the normality tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for sit-to-stand, stand-to-sit, and walking motor tasks of TUG, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Tests of Normality		
TUG	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	T1	T2
Sit-to-stand		
DispAP_Stand	.200*	.200*
DispML_Stand	.162	.200*
VelMinAP_Stand	.200*	.200*
VelMaxAP_Stand	.200*	.097
VelMinML_Stand	.175	.024
VelMaxML_Stand	.200*	.200*
Walking		
DispAP_Walk	.200*	.200*
DispML_Walk	.185	.200*
VelMinAP_Walk	.200*	.200*
VelMaxAP_Walk	.057	.200*
VelMinML_Walk	.200*	.200*
VelMaxML_Walk	.032	.200*
Stand-to-sit		
DispAP_Sit	.200*	.081
DispML_Sit	.200*	.200*
VelMinAP_Sit	.200*	.200*
VelMaxAP_Sit	.200*	.200*
VelMinML_Sit	.136	.200*
VelMaxML_Sit	.021	.200*
*. This is a lower bound of the true significance.		
a. Lilliefors Significance Correction		

Table 0.21 - The p-values of the normality tests for BBS and TUG scores, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Tests of Normality		
Clinical Tests	Kolmogorov-Smirnov	
	Sig.	
Motor tasks	Pre	Post
BBS	.000	.000
TUG	.175	.180

Table 0.22 - The p-values of the homogeneity test for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for CS, and CF motor tasks of the virtual challenge “Fruit Catcher”, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Test of Homogeneity of Variance	
Catch Fruit	Levene
	Sig. (Based on mean)
Motor tasks	
Climbing Stairs	
DispAP_CS	.035
DispML_CS	.535
VelMinAP_CS	.847
VelMaxAP_CS	.400
VelMinML_CS	.441
VelMaxML_CS	.854
Catching Fruits	
DispAP_CF	.430
DispML_CF	.507
VelMinAP_CF	.255
VelMaxAP_CF	.537
VelMinML_CF	.410
VelMaxML_CF	.077

Table 0.23 - The p-values of the homogeneity tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for EB, and standing on one leg inside the bathtub (IB) motor tasks of the virtual challenge “Take a Shower”, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Test of Homogeneity of Variance	
Take a Shower	Levene
	Sig. (Based on mean)
Motor tasks	
Entering in the bathtub	
DispAP_EB	.794
DispML_EB	.486
VelMinAP_EB	.451
VelMaxAP_EB	.971
VelMinML_EB	.193
VelMaxML_EB	.221
Standing on one leg	
DispAP_IB	.375
DispML_IB	.335
VelMinAP_IB	.404
VelMaxAP_IB	.761
VelMaxML_IB	.266

Table 0.24 - The p-values of the homogeneity tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, collecting food from the kitchen shelves of the virtual challenge “Cooking”, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Test of Homogeneity of Variance	
Cooking	Levene
	Sig. (Based on mean)
Motor tasks	
Pick up the food	
DispAP_Cook	.895
DispML_Cook	.553
VelMinAP_Cook	.293
VelMaxAP_Cook	.019
VelMinML_Cook	.928
VelMaxML_Cook	.529

Table 0.25 - The p-values of the homogeneity tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for stand-to-sit, sit-to-stand, and walking motor tasks of the virtual challenge “Watch Tv”, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Test of Homogeneity of Variance	
Watch TV	Levene
	Sig. (Based on mean)
Motor tasks	
Stand-to-sit	
DispAP_Sit	.542
VelMinAP_Sit	.128
VelMaxAP_Sit	.500
VelMinML_Sit	.180
VelMaxML_Sit	.041
Sit-to-stand	
DispAP_Stand	.969
DispML_Stand	.963
VelMinAP_Stand	.276
VelMaxAP_Stand	.024
VelMinML_Stand	.881
VelMaxML_Stand	.413
Walking	
DispML_Walk	.072
VelMinAP_Walk	.775
VelMaxAP_Walk	.840
VelMinML_Walk	.594

Table 0.26 - The p-values of the homogeneity tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for BBS motor tasks, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Test of Homogeneity of Variance	
BBS	Levene
	Sig. (Based on mean)
Motor tasks	
Sit-to-stand	
DispAP_BBS1	.103
DispML_BBS1	.147
VelMaxAP_BBS1	.107
VelMinML_BBS1	.744
VelMaxML_BBS1	.818
Standing unsupported	
DispML_BBS2	.804
VelMaxAP_BBS2	.424
VelMaxML_BBS2	.294
Sitting unsupported	
DispML_BBS3	.258
VelMinAP_BBS3	.524
VelMaxAP_BBS3	.791
VelMinML_BBS3	.920
Stand-to-sit	
DispAP_BBS4	.637
DispML_BBS4	.698
VelMinAP_BBS4	.634
VelMaxAP_BBS4	.878
VelMinML_BBS4	.298
VelMaxML_BBS4	.874

Test of Homogeneity of Variance	
BBS	Levene
	Sig. (Based on mean)
Motor tasks	
Transfers	
DispAP_BBS5	.483
DispML_BBS5	.114
VelMinAP_BBS5	.666
VelMaxAP_BBS5	.399
VelMinML_BBS5	.081
Standing with eyes closed	
DispAP_BBS6	.630
DispML_BBS6	.169
VelMinAP_BBS6	.949
VelMaxAP_BBS6	.933
VelMaxML_BBS6	.131
Standing with feet together	
DispAP_BBS7	.606
VelMinAP_BBS7	.987
VelMaxAP_BBS7	.836
VelMinML_BBS7	.531
Reaching forward	
DispAP_BBS8	.959
DispML_BBS8	.817
VelMinAP_BBS8	.594
VelMaxAP_BBS8	.564
VelMaxML_BBS8	.656

Test of Homogeneity of Variance	
BBS	Levene
	Sig. (Based on mean)
Motor tasks	
Pick up an object	
DispAP_BBS9	.787
DispML_BBS9	.784
VelMinAP_BBS9	.648
VelMaxAP_BBS9	.567
VelMinML_BBS9	.839
VelMaxML_BBS9	.483
Looking over shoulders	
DispAP_BBS10	.140
DispML_BBS10	.451
VelMaxAP_BBS10	.610
VelMinML_BBS10	.800
VelMaxML_BBS10	.842
Turn 360 degrees	
DispAP_BBS11	.844
DispML_BBS11	.853
VelMinAP_BBS11	.267
VelMaxAP_BBS11	.153
VelMinML_BBS11	.291
VelMaxML_BBS11	.152
Place alternate foot on step	
DispAP_BBS12	.257
DispML_BBS12	.002
VelMinAP_BBS12	.351
VelMaxAP_BBS12	.691
VelMaxML_BBS12	.518

Test of Homogeneity of Variance	
BBS	Levene
	Sig. (Based on mean)
Motor tasks	
Standing with one foot in front	
DispAP_BBS13	.249
DispML_BBS13	.000
VelMinML_BBS13	.239
VelMaxML_BBS13	.224
Standing on one leg	
DispML_BBS14	.620
VelMinAP_BBS14	.308
VelMaxAP_BBS14	.548
VelMinML_BBS14	.814
VelMaxML_BBS14	.337

Table 0.27 - The p-values of the homogeneity tests for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions, for sit-to-stand, stand-to-sit, and walking motor tasks of TUG, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Test of Homogeneity of Variance	
TUG	Levene
	Sig. (Based on mean)
Motor tasks	
Sit-to-stand	
DispAP_Stand	.970
DispML_Stand	.527
VelMinAP_Stand	.749
VelMaxAP_Stand	.396
VelMaxML_Stand	.226
Walking	
DispAP_Walk	.614
DispML_Walk	.488
VelMinAP_Walk	.925
VelMaxAP_Walk	.263
VelMinML_Walk	.441
Stand-to-sit	
DispAP_Sit	.423
DispML_Sit	.580
VelMinAP_Sit	.688
VelMaxAP_Sit	.548
VelMinML_Sit	.610

Table 0.28 - The p-value of the homogeneity test for TUG scores, considering a significance level of 5 %. The most representative results (p -value < 0.05) appear in bold

Test of Homogeneity of Variance	
Clinical Test	Levene
	Sig. (Based on mean)
TUG	.324

APPENDIX III – USER’S EXPERIENCE EVALUATION

Figures 0.1 and 0.2 present the results of each participant in each factor and subscale of IPQ and IMI tests, respectively.

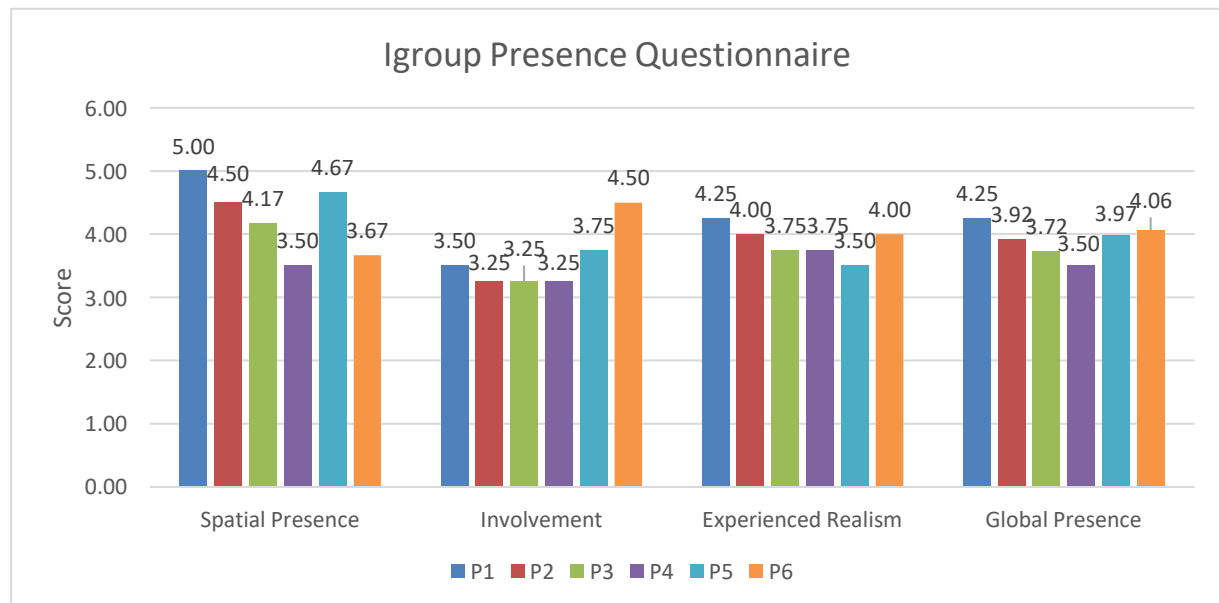


Figure 0.1 - Scores of the Spatial Presence, Involvement, Experienced Realism, and Global Presence of the IPQ for the six participants.

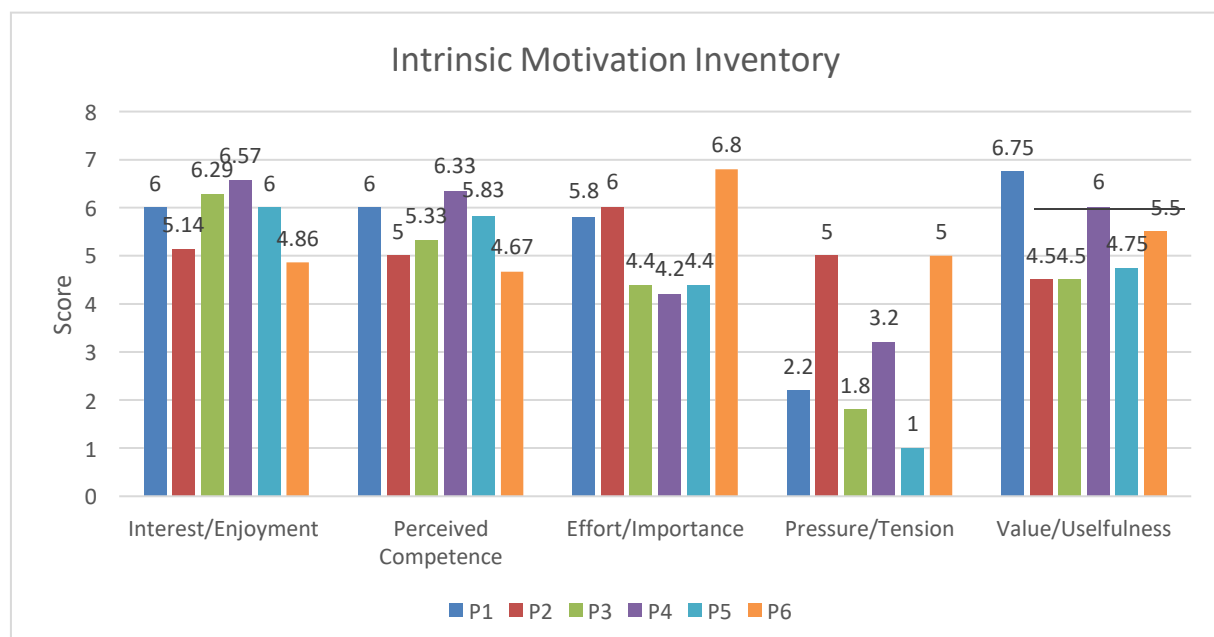


Figure 0.2 - Scores of the Interest/Enjoyment, Perceived Competence, Effort/Importance, Pressure/Tension, and Value/Usefulness of the IMI questionnaire for the six participants.