POLITECNICO DI TORINO

Master's Degree in BIOMEDICAL ENGINEERING

Master's Degree Thesis

Design and Development of a Dual-Task Exergame with Avatar-Based Coaching for Patients at Risk of Mild Cognitive Impairment

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Summary

This master's thesis is conducted within the framework of a broader European research initiative, the Dorian Gray project, exploring the correlation between Mild Cognitive Impairment (MCI) and Cardiovascular Diseases (CVDs). The European project adopts a multidomain approach that combines MCI risk monitoring with physical exercise and cognitive training.

Recent studies have highlighted the role of CVD symptoms in damaging brain structures and its vascular network, thus suggesting that these may act as risk factors in the onset of dementia. Physical inactivity in the ageing population should be addressed as a key variable: it can double the risk of developing dementia later in life if not accounted for. In this context, the thesis project focuses on the gamification of physical and cognitive training to promote long-term engagement and adherence.

Given the importance of targeting flexibility, strength, and cardiovascular fitness while simultaneously stimulating cognitive function, the proposed solution consists of an exergame implementing dual-task exercises. Specific fitness movements have been chosen to aim at full-body exercise, to be completed concurrently with memory and attention tasks.

To ensure usability and optimal user experience, the exergame is designed for mobile devices, specifically for Android tablets (Samsung Galaxy Tab S9 FE or similar), and utilises the device's video stream from the frontal camera. The QuickPose framework has been employed to integrate one of MediaPipe's pose estimation models and gesture recognition techniques to track and classify physical movements.

In addition, the project implements patient's embodiment through a personalised avatar representing the user in the game environment according to their preferences. To further promote engagement, the tracked movements are employed to animate the avatar in real-time. Feedback mechanisms were designed to operate both in the short term, through timely responses during gameplay, and in the long term, by supporting the monitoring of progress over time.

An avatar-based digital coach is predisposed to guide the patient through the lifestyle intervention, demonstrating the exercises to complete and encouraging

correct execution. The coach provides supportive verbal feedback and remarks on movement form during task performance, further promoting engagement and long-term adherence.

After development, a preliminary testing of the exergame was performed to evaluate its usability and investigate key features like immersion, presence, and user perceived competence. The system was tested with $n = 27$ predominantly young participants, largely with higher-education backgrounds. Usability assessment resulted in a mean SUS score of 81.2 ($\sigma = 11.02$), placing the system in the *Good–Excellent* range and confirming its overall acceptability. Additionally, task performance showed significant improvement after the first trial ($p < 0.001$), indicating that participants understood the game directives and gained confidence with continued play. Furthermore, real-time avatar animation was highlighted as the most immersive feature, supporting engagement alongside the presence of the digital coach.

This work integrates multiple design features to demonstrate the technical feasibility of engaging exergames, showing preliminary usability and pointing to immersive, presence-enhancing features as a promising topic for future research.

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Acronyms

AD

Alzheimer's Disease

ADL

Activities of Daily Living

AI

Artificial Intelligence

$APOE^{*}\epsilon 4$

Apolipoprotein gene, epsilon 4 allele

BADL

Basic Activities of Daily Living

CVD

Cardiovascular Disease

DC

Digital Coach

DT

Dual-Task

DTE

Dual-Task Effect

DTT

Dual-Task Training

FOV
: Field Of View

GDS
: Global Deterioration Scale

HFOV
: Horizontal Field Of View

IADL
: Instrumental Activities of Daily Living

IQR
: Interquartile Range

MCI
: Mild Cognitive Impairment

PENS
: Player Experience of Need Satisfaction

QP
: QuickPose

RPM
: Ready Player Me

SUS
: System Usability Scale

T4A
: Tracking4All

TTS
: Text-To-Speech

XP
: Experience Points

Chapter 1

Introduction

1.1 Mild Cognitive Impairment

Mild Cognitive Impairment (MCI) is a syndrome that describes a state of cognitive deficit not yet meeting the criteria of dementia [1]. Characterised by a cognitive decline higher than expected for people of the same age and education level, the measurable deficits often include memory complaints and further encompass multiple areas of cognition, even if functionality in activities of daily life is still largely preserved [2]. Historically, MCI is defined for the first time by the Global Deterioration Scale (GDS): the scale distinguishes seven clinical stages, from normality to mild dementia, and associates Stage 3 with MCI, as defined in Table 1.1, by subtle deficits in cognition and possibly impairments in demanding social and occupational activities. MCI can be further divided in *amnestic* and *non-amnestic* MCI, based on the key deterioration of the memory function [3, 1, 2].

The incidence of MCI in people over the age of 60 is between 12% and 18% [4], and even though the causes of this syndrome are not completely understood, the most relevant risk factors are advancing age, family history of dementia, neurodegenerative features and conditions that are linked with cardiovascular disease [4, 1]. The progression of this pathology to Alzheimer's Disease (AD) is variable and led by multiple factors, with approximately 10-15% of *amnestic* MCI patients developing AD every year, as opposed to 1-2% of healthy older adults [3]. Nevertheless, research shows that even people reverting to normal condition are still at higher risk of progressing to a form of dementia in the subsequent years, with this statistic worsening in the presence of the epsilon 4 allele of the apolipoprotein gene ($APOE^{*}\epsilon4$), risk factor for AD.

Fundamental is the link between MCI and Cardiovascular Disease (CVD): recent studies have highlighted the role of CVD symptoms in damaging brain structures and its vascular network, thus suggesting that these may act as risk factors in the

Table 1.1: Global Deterioration Scale (GDS): Stages and Characteristics

Stage	Main Characteristics
Stage 1: No Cognitive Decline	No complaints of memory loss. Normal functioning in all domains. No clinical evidence of decline.
Stage 2: Very Mild Cognitive Decline (Subjective Cognitive Impairment)	Occasional memory lapses (e.g., forgetting names or object locations). No objective deficits on testing.
Stage 3: Mild Cognitive Impairment (MCI)	Measurable memory or cognitive deficits. Problems with concentration and planning may impact work or daily routines. Clinically detectable.
Stage 4: Moderate Cognitive Decline (Mild Dementia)	Difficulty with complex tasks (e.g., managing finances, traveling alone). Personality changes and denial of problems may emerge.
Stage 5: Moderately Severe Cognitive Decline (Moderate Dementia)	Requires help with daily activities. Forgets personal details (e.g., address). Retains own name and identity. Dressing assistance often needed.
Stage 6: Severe Cognitive Decline (Severe Dementia)	Loses awareness of recent events. Needs help with basic tasks (bathing, dressing). Behavioral symptoms like delusions or sleep issues may appear.
Stage 7: Very Severe Cognitive Decline (Late Dementia)	Loss of verbal and motor skills. Requires full-time care. May become unresponsive. All activities of daily living must be assisted.

onset of dementia. Artery occlusions, brain infarcts and microbleeds, along with atrial fibrillation, can be vascular causes of cognitive impairment, as consequences of altered cerebrovascular perfusion [5, 6]. Moreover, the same $APOE^{*}\epsilon 4$ can be linked to reduced cerebral blood flow, thus acting in synergy with other vascular risk factors in the relationship between MCI and CVD [7]. Figure 1.1 schematically represents contributors and consequences of MCI, highlighting the decline in cognitive domains such as memory, attention, and executive function, which in turn compromise independence and quality of life.

Regarding the management of MCI, pharmacological intervention is not the most successful approach, as its efficacy is predominantly associated with a significantly elevated risk of AD [1, 2]. As a consequence, preventing MCI is of utmost importance, leading the research towards cognitive training and lifestyle modifications. In this regard, the suggestions for aging people affected by either CVD or at risk of MCI are similar: to avoid smoking and unhealthy nutrition, along with exercising regularly; in fact, physical inactivity leads to an almost twofold higher risk of developing dementia in later years [8, 6]. This thesis project explores a possible intervention for people at high risk of MCI, combining cognitive training and physical activity, which is regarded as a central variable to be modified in everyday habits.

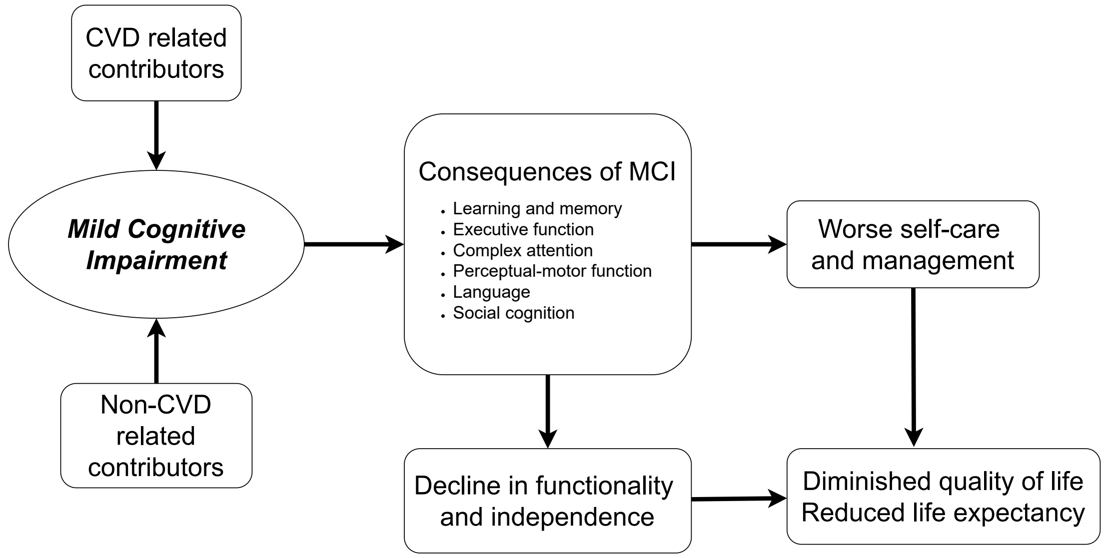


Figure 1.1: Overview of Mild Cognitive Impairment (MCI), its cardiovascular and non-cardiovascular contributors, and its cognitive and functional consequences. The diagram highlights the wide-ranging impact of MCI on individuals' health, autonomy, and quality of life.

1.2 Exergames

Exergames, or exertion games, are videogames that translate physical movement into game commands, requiring players to engage in bodily effort to progress. They typically involve active tasks such as running, dancing, performing fitness or other sport-like motions [9, 10].

Originally popularised by entertainment platforms like Nintendo's *Wii Fit*, exergames have since gained considerable attention in healthcare and rehabilitation due to their capacity to promote physical activity in an engaging and enjoyable format [11, 12]. Over the past years, numerous studies have demonstrated the growing effectiveness of exergaming interventions in achieving health-related goals: these games are associated with increased energy expenditure and can engage individuals who may not otherwise participate in traditional forms of exercise [9, 13, 14]. The value of exergames as training tools lies in the heightened appeal that they can generate in users: providing a novel and inherently entertaining way of exercising could promote patients' adherence to an intervention program, while also increasing the effectiveness of it.

Among older demographics, research suggests that exergames can be effective in improving balance, mobility, and cognitive function, therefore being often used to support fall prevention, encourage regular exercise, and enhance mental stimulation, making them a promising tool for supporting both physical and cognitive health in aging populations [14, 15, 16].

1.2.1 Patient Embodiment

Research shows that embodiment should be regarded as a key design variable during the development of an exergame that aims to promote patient commitment and lifestyle changes. The portrayal of the user's body and their sensory and motor engagement with the interface generates different feelings: presence, or sense of being in the game, can be enhanced by realistic virtual and auditory cues; and enjoyment, that emerges when the task appropriately balances challenge and skill, maintaining user attention and engagement [11]. Higher levels of in-game embodiment are associated with increased feelings of presence and enjoyment, leading in turn to higher energy expenditure during gameplay; as a result, the patient would feel more committed to the training program, increasing the probability of sustained exergame use and thus evoking the behavioral change that is the objective of the intervention [11, 17].

Moreover, an important factor to take into account is how the patient could be represented in-game: it's been shown that self-perception can influence attitude and behaviours inside the game, but more importantly, outside of it [11, 18]. For instance, a study conducted in 2014 demonstrated that overweight participants who played using avatars with a normal weight body type (see Figure 1.2a) not only performed better in the physical tasks but also reported greater motivation to continue playing and exercising [19]. This phenomenon provides an example of the *Proteus Effect*: users observe their virtual appearance and are influenced by it, modifying their behaviour on the basis of identity cues derived from the graphical representation of their avatar [18].

Furthermore, the avatar should not appear overly human or realistic so as to try and avoid the *Uncanny Valley Effect*: feelings of uneasiness can be linked to avatars that look too anthropomorphic, with users having a preference for cartoony or simplified human features [17, 20]. In addition, to avoid unintended stereotyping of the user, it is advisable to offer a high degree of customization rather than presenting a limited set of avatar presets, which may fail to resonate with all users [21]. For this reason, a viable option is to initiate character creation from the actual appearance of the patient, for example, through a user-provided photo, while allowing further customization. To balance this personalization with the need to prevent uncanny visual discomfort, the avatar's appearance can be rendered in a cartoony or stylized form, maintaining recognizability without overly realistic features. This enables users to determine how they wish to be represented in-game, potentially selecting an aspirational or motivational body type aligned with their personal view of athleticism, further producing a positive attitude toward the training experience. An example of customization interface is presented in Figure 1.2b.

(a) **(b)**

Figure 1.2: a) Normal body size and large body size in-game avatars used in [19]. b) Depiction of the Avatar Customization in Ring Fit Adventure (Nintendo Switch).

1.2.2 Pose Estimation

In the context of 3D human kinematics and the measurement of human motion, pose estimation refers to the computer vision task of identifying and tracking key points (landmarks) on the body to infer spatial orientation of joints. It mainly features machine learning methods and is described as markerless motion capture [22].

Regarding exergames and remote interventions, a crucial aspect to be considered is the method used for pose estimation. The goal is to ensure independent use of the game at home, with satisfactory accuracy in the measurements to provide a smooth experience and correct feedback to the patients on the movements used as inputs for the game. Table 1.2 illustrates different motion capture and pose estimation techniques used in exergames, ranging from high-precision marker-based systems to low-cost, camera-based deep learning approaches [22, 23, 24].

Some of the most popular technologies for pose estimation in exergames involve the use of hand-held controllers using inertial sensors or input boards with pressure sensors [25]. While these solutions offer precise tracking, they require constant physical interaction with the device and the use of specialized video game consoles. Such restrictions could represent usability issues for elderly people, who might not be familiar with gaming technology or find these interfaces inconvenient.

Table 1.2: Comparison of motion capture and pose estimation technologies used in exergames.

Technology Category	Description / Examples	Role in Exergames
Marker-Based Motion Capture	High-precision 3D tracking using reflective markers and infrared cameras (e.g., Vicon, OptiTrack).	*Gold-standard accuracy*; used in laboratory or clinical settings due to cost and complexity.
Sensor-Based Systems	Inertial or pressure-based consumer devices (e.g., Wii Remote, Wii Balance Board).	Accurate for localized tracking but constrains movements to specific hardware setups.
Vision-Based (Depth/RGB-D)	RGB + depth sensors (e.g., Microsoft Kinect) combining infrared projection and RGB imaging.	Provides 3D joint data without wearables; affordable but requires external hardware.
Vision-Based (Single RGB)	Standard cameras with DL-based models (e.g., OpenPose, DeepLabCut, MediaPipe).	Low-cost, markerless solution for home use; estimates 2D pose or infers 3D via model reconstruction.

In contrast, the use of gesture recognition leveraging the RGB camera feed allows users to control the game naturally, eliminating the need for a controller. Multiple studies have analyzed the efficiency of vision-based systems as input controls for exergames, highlighting the promising results of these low cost systems both in terms of accuracy and ease of use [25, 26, 27]. From this perspective, it arises the need to accurately track the patient's movements and classify them according to the estimation of body landmark positions and joint rotations.

1.2.3 Feedback, Challenge and Rewards

Central components of any exergame are *feedback*, *challenge*, and *rewards*: intentionally designed to enhance user enjoyment and motivation, they are key elements to ensure continued long-term engagement and physical activity in patients [28, 29, 30].

Feedback plays a fundamental role in supporting the user's perception of their competence in successfully completing in-game tasks by offering clear information on performance, skill development, and progress. Timely and meaningful feedback, in addition to intuitive game controls and optimal challenge level reinforces the patient's sense of improvement and efficacy, which can promote continued participation [28, 31].

Closely tied to feedback is the concept of *challenge*, which must be carefully calibrated to match the user's skill level. An optimal balance fosters a sense of progression and generates opportunities for positive reinforcement. When challenge is appropriately balanced, it can lead to a *flow state*, where the difficulty of the task aligns with the user's abilities, resulting in a highly immersive and intrinsically motivating experience [29]. Figure 1.3 illustrates a model of flow in which the game accommodates fluctuations in performance, taking into account failure and frustration, while avoiding boredom through gradual, though not continuous, increases in difficulty. This dynamic engagement enhances feelings of autonomy and competence, particularly when paired with intuitive controls.

Rewards, when used effectively, serve as an additional motivational tool. However, they must be implemented carefully: if used merely as external incentives, they risk shifting the player's focus solely toward reward achievement rather than meaningful behavior change. To support long-term engagement and lifestyle transformation, rewards should be framed as informational feedback rather than as controlling mechanisms. For example, performance-based rewards of glory (e.g., trophies, badges) can strengthen perceptions of competence and relatedness, while narrative rewards, often absent from exergames, can enhance immersion and reinforce agency by linking progress to story elements, thus reducing monotony and enriching the user experience [29].

In terms of delivery, feedback should favor *audio* and *visual* modalities over text, as older adults may struggle to read small or distant on-screen text [32]. Audio feedback, in particular, enhances presence and realism, boosts performance, and supports "juicy" game design, the providing of rich, positive, and continuous cues that make gameplay immediately gratifying [33].

To complement in-game feedback, performance data can be summarized in post-session reports, offering additional insights and progress metrics without disrupting gameplay.

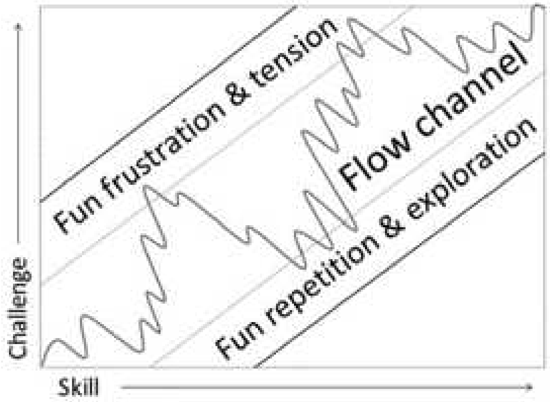


Figure 1.3: An adapted model of *Flow* in exergames proposed in [29].

1.3 Dual-Task Exercises

Numerous daily activities require both motor and cognitive activities to be completed concurrently: for example, crossing the street while looking at the traffic flow or cooking and planning how to execute the next step of a recipe. A Dual-Task (DT) paradigm involves the sharing of cognitive resources between two tasks with independent goals, that can be evaluated separately with different outcome measures.

Task performance decreases when a secondary, usually cognitive, task is introduced, highlighting the Dual-Task Effect (DTE): an additional cost on the cognitive reserve diminishes the capacity to achieve the goal of the primary task [34, 35]. This effect is especially present in aging people, who show more pronounced difficulties in DT situations, leading to such paradigms being used as a clinical tool: from evaluating increased risk of falling to marking cognitive impairment or the presence of AD [35, 36, 37]. Several theories have been proposed to explain the DTE: the *central capacity sharing* theories assume the presence of a fixed capacity processor to be shared by the tasks, causing one to be damaged in performance when allocated with less resources; the *bottleneck model* posits, instead, the possibility of only processing one activity at a time, thus causing the delay or the impairment of the other [36]. In this context, and in light of aging mechanisms like sensory loss and diminished automated motor/cognitive performance, older people would have access to a reduced capacity and processing efficiency. It has been demonstrated in recent decades that regular motor and cognitive Dual-Task Training (DTT) can enhance the cognitive and motor abilities of older persons, freeing up resources previously used to monitor one or both of the tasks, that can be consequently used to improve performance in the DT condition [35, 38, 39, 40].

Numerous studies have examined the effects of combining physical and cognitive exercises in DTT, implemented either as *simultaneous training*, where both components are delivered concurrently in a dual-task format, or as *sequential training*, with cognitive and physical exercise delivered separately, potentially on different days [41, 42, 43]. Exergaming inherently provides a promising platform to integrate physical exercise with cognitive challenges. Evidence supports the use of *simultaneous training*, which can enhance efficacy compared to single-task training, even when delivered at a lower dose than *sequential training* [41].

Furthermore, the *Moving while Thinking* framework suggests eliminating task prioritization or adaptation processes by embedding cognitive tasks as prerequisites for completing motor actions, rather than treating them as distractors or secondary tasks; an example of this is walking while solving a navigational memory task [43]. This integration promotes higher adherence by more closely mirroring real-life contexts, for instance, the previous example could simulate walking through a supermarket while remembering what items to buy and where to find them, thereby making the activity more meaningful to patients and reinforcing the effectiveness of *simultaneous training*.

In the process of designing training for people at risk of Mild Cognitive Impairment (MCI), research shows an interest in exercises that are close to real-life situations, both so that they can be seen as relevant by the patient and in light of task-specific brain adaptations, to induce cognitive transfer effects to daily living functions [43].

Specifically, there is a link between MCI and the loss of efficiency in Instrumental Activities of Daily Living (IADL) [44, 45]. While Basic Activities of Daily Living (BADL) comprehend fundamental tasks necessary to take care of basic physical needs such as personal hygiene, dressing, ambulating and eating, the IADL encompass more complex activities such as shopping, meal preparation, home maintenance and using public transportation [45, 46]. Incorporating physical or cognitive tasks related to IADL in the training has shown positive effects on executive function and IADL performance in MCI patients, thus supporting the adoption of a similar approach in this project, aimed at preventing the progression of cognitive decline [47, 48].

Typical physical exercises implemented for exergames range between resistance and aerobic training, balance and coordination, dancing. Among these, resistance training has demonstrated superior effects on cognitive performance and requires a lower training dose to yield benefits compared to aerobic exercise [42, 49].

Cognitive exercise can be devised to directly target markers of dementia risk, stimulating visual and verbal episodic memory, verbal recognition memory, or mathematical thinking, with improvements in this area impacting everyday tasks required for independence [42].

1.4 Digital Coaching

Digital coaches (DC) are tools becoming increasingly relevant in a variety of domains to complement (and sometimes substitute) human coaching, reduce management costs of programs to improve wellbeing and expand user base [50, 51]. From guiding physical training to improving awareness in the nutritional sphere, the main goal of a virtual coach is to support the user in reaching their goal and provide motivation. These systems should be able to determine user intent, extrapolate information from context cues and therefore supply useful feedback on how to improve in a certain lifestyle's area.

Especially in the context of exergames, the DC should also offer companionship to the user: providing a form of social connection in the role of an expert companion can encourage and motivate the patients, leading to increased determination in achieving the goal and higher perceived competence [52]. Socially engaging interactions of this type can raise self-esteem, allowing for more confidence in reproducing correct behaviours, even resulting in increased physical activity with respect to interventions that lack a DC [51]. Moreover, the presence of a DC in the exergame can guide the player through the physical motions, acting as a model to emulate and thus allowing first *vicarious learning* through observation and then *enactive learning*, with the user experiencing and acting out the exercise [52].

To ensure the social presence of the DC, an avatar-based implementation is necessary, as the sole verbal interaction through speech has inferior efficacy [53, 51]. The appearance of anthropomorphic agents is a key variable in users making assumptions on their status and credibility: to be believable they have to fit in the context of the game world, expressing emotions with an appropriate voice and interacting adaptively with non-verbal cues like gesturing and facial expressions. Research generally supports the use of a DC of similar age, gender and ethnicity to the patient, as especially older adults look for a role model in aging, to represent ideal criteria of aging success or at least an image of strong perseverance through difficulties [53, 54]. On the contrary, using an overly expert figure like a master athlete could be detrimental, with older adults preferring a DC that acts more as a peer, with realistic and attainable features, so as to promote mutual engagement mechanisms [54].

Providing feedback through a coach figure can satisfy older patients' need for social interaction while providing useful information about performance. As shown in [31], positive verbal feedback from an active virtual audience can improve user experience and performance, this being further confirmed by the findings in [10], where a positive attitude of the DC results in higher satisfaction of the users' need for competence, rendering them more attentive and prone to judge the activity as more "fun". Thus, a DC should be implemented in the game to comment when an exercise is performed correctly or when a subgoal has been achieved. The coach must meet two key criteria: it must be *personalized*, tailoring feedback to the user's performance and characteristics; and *context-aware*, offering *just-in-time* training [50, 55]. This requires integrating performance data from both the physical and cognitive components of the game, with outcome measures derived from real-time analysis of movement features (e.g., joint angles, positions, velocities) informing the timing and content of the coach's remarks [32].

DC systems in healthcare commonly feature various hardware components for their implementation, typically monitoring user activities by relying on step counters and detection algorithms that recognize movements, speech, posture, gestures, and emotions [50]. Wearable sensors and mobile devices, in particular, are frequently utilized in in-home coaching to promote physical activity and healthier lifestyles among older adults. Kinect 3D cameras have also been a significant technology, enabling advanced functionalities like unobtrusive monitoring of whole body movement and precise user-system interaction for exercise and rehabilitation, allowing for precise feedback and evaluation [56].

To achieve the personalisation in the interaction between DC and patient necessary to create a more immersive and engaging experience, it is essential to effectively extract meaningful information from these hardware components with the goal of dynamically adapting the coaching based on sensing input data. Nevertheless, a significant challenge still persists in providing real-time feedback back to the user [56]: while mobile implementations are widely recognized as common and efficient for use in diverse contexts, including for elderly populations familiar with smartphone app's usage [50, 51], they still need to be further explored to offer more automated and precise feedback.

1.5 Objectives

The central concept of this thesis revolves around the design and development of an exergame-based intervention specifically tailored to address the cognitive and motivational challenges associated with aging.

Within this framework, two main objectives are pursued: first, the creation of a functional application that integrates multiple design features into a coherent system, and second, the evaluation of this prototype in terms of usability and user experience.

1. **Design and Development of an Integrated Exergame Application:** The first objective is the design and implementation of a functional prototype of an Android-based exergame that combines several interdisciplinary elements into a single tool designed specifically to enhance user engagement and support cognitive stimulation in aging populations at risk of MCI. The application integrates:

    - **Kinematics tracking and task classification:** Implement a system to continuously capture and analyze the patient's full-body movements using the webcam of an Android mobile device. This system should be capable of accurately identifying and classifying different exercises or tasks being performed by the patient in real time.
    - **Patient's avatar:** Create a digital embodiment of the patient within the exergame environment, driven by the tracked body movements. The avatar should mirror the patient's actions to provide immediate visual feedback and enhance immersion.
    - **Dual-task exergame development:** Design and implement an interactive exergame that incorporates both physical and cognitive challenges to stimulate motor and mental function simultaneously in a Dual-Task paradigm.
    - **Avatar-based coach interaction:** Develop a digital coach represented as an animated avatar capable of interacting with the user. The coach should lay the groundwork for a coaching system able to provide guidance and social support to the training experience.
    - **Progress tracking:** Integrate a functionality to record and analyze the user's performance throughout each session.
    - **Motivational and feedback systems:** Integrate the exergame with mechanisms to promote engagement and boost adherence to the training schedule.

2. **Evaluation of Usability and User Experience:** As a consequence of the design and development effort, the second objective is to conduct an exploratory user study aimed at validating the design choices and the implementation results. The evaluation focuses primarily on usability, while also investigating aspects of the user experience specifically related to presence, immersion, competence, and embodiment.

In summary, the comprehensive goal of this thesis is to demonstrate the technical feasibility of combining physical and cognitive exercise, along with digital coaching, within a mobile exergame but also to draw on real user testing to identify which features hold the most promise for designing engaging and effective interventions for aging populations at risk of cognitive decline.

Chapter 2

Design of the Dual-Task Exergame

2.1 Design considerations for older adults with MCI risk

In light of the context given in the preceding chapter, this work focuses on the development of a complete exergame, with the goal of showcasing the possible integration of a series of features aimed at the enhancement of motivation, engagement and the adherence to this gaming and prevention experience.

The main issue addressed in this work is the specific implementation of a dual-task (DT) paradigm for individuals over 60 years old who are at risk of mild cognitive impairment (MCI). Adapting to the technical requirement of using a mobile device, and privileging full-body exercises, directed the project toward identifying feasible activities that are not overly strenuous yet remain effective. Particular attention was given to grounding the selected exercises in realistic tasks, as exemplified in [47, 48], with the aim of explicitly targeting activities that offer a high potential for transfer to Activities of Daily Living (ADLs). With this goal, the project sought to leverage the RGB frontal camera of the tablet to implement a gesture recognition algorithm, offering a novel mode of interaction for the older population. Section 2.1.2 will delineate the design choices behind the paradigm adopted in this project.

The second aspect considered, given the older population targeted, is the need to apply techniques aimed at maintaining engagement of the users: inherent in the use of an exergame for the prevention of MCI is the requirement for the system to provide not only an effective training tool but also an enjoyable experience. User enjoyment in interacting with the application must therefore be regarded as a central variable: the following sections will outline the choices and concepts aimed at increasing engagement and the eventual adherence to the intervention.

2.1.1 Patient embodiment

The following approach has been chosen in order to maximize the patient's feeling of presence in the game environment and promote a more positive and motivated attitude toward the training process.

Avatar Creation

The first design choice allows for users to be represented in the game by a custom avatar, which they can personalize to ensure it accurately reflects their preferred appearance within the game. To enhance embodiment, character creation ideally begins with a photograph of the patient, ensuring facial resemblance and promoting self-identification with the avatar. For older adults, an additional advantage in generating the avatar from a photo lies in the simplification of the process: instead of building the character from scratch and employing conspicuous time learning to use the tool and surveying all the possible choices, a first resemblance is obtained in seconds and, if needed, the user can adjust some of the features, without losing themselves in too extensive customisation. The visual style of the avatar is cartoony but still clearly anthropomorphic, reaching a balance between relatability and avoidance of the *Uncanny Valley* effect. Users are able to customise key aspects of their avatar's appearance, such as body shape and attire, allowing for personalization that aligns with individual preferences and motivational factors, thus providing the best possible user representation, with reduced risk of incurring in stereotyped portrayal.

In this context, a promising tool is found in Ready Player Me [57]: the open source platform supports avatar generation from a selfie and provides an intuitive customization interface (see Figure 2.1). It privileges stylised shapes while still being realistic and features a vast variety of choices for face characteristics, body frames and clothing.

Avatar Animation

In exergames like *Wii Fit* and *Ring Fit Adventure* [58, 59], which utilise sensor-based input devices, the user's motions are typically mapped to pre-recorded animations, ensuring smooth and visually appealing movements even if the player's motion is imprecise. In contrast, depth- and vision-based systems, such as the *Kinect* [60], track a user's full-body skeleton in real time, allowing the avatar to partially or fully mimic the player's actions, while still employing pre-recorded animations for certain complex or stylized motions.

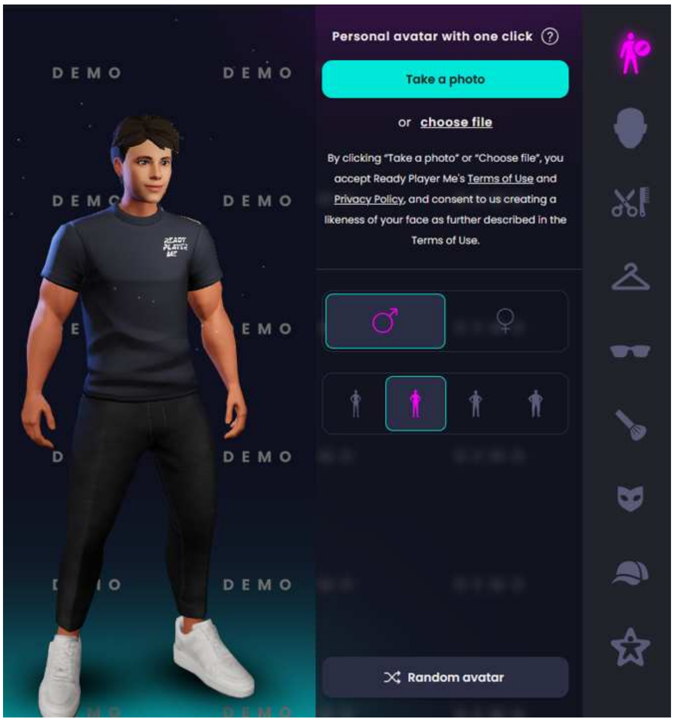


Figure 2.1: Ready Player Me interface for avatar creation from photo and further customization.

Since our system relies on an RGB tablet camera, and to further promote immersion in the game environment, it was decided to opt for a body tracking solution: the chosen approach works to increase the user's feeling of presence while providing direct feedback on their movements. A pose estimation method is employed to track body motions and thus extract the data necessary to reproduce them in the game engine. As a result, the patient's avatar replicates the exact same movements in real-time, following limb, head and torso position and rotation.

2.1.2 Dual-Task Exercises

Physical Training and Visual Episodic Memory

In light of the findings discussed in Section 1.3, the DT exergame proposed in this project focuses on resistance training for older adults, paired with a cognitive component targeting visual episodic memory.

Specifically, the cognitive task takes the form of an item recollection activity [61, 62]: in the game session, participants are presented with a sequence of object figures which they will be required to recognize shortly after by selecting the correct item from different options. More specifically, each selection will be made by performing a certain physical movement, associating the items with a resistance-based exercise. The design aimed to make movement an integral part of gameplay by incorporating the stepping in place, squatting, and overhead presses motions to control navigation and item selection within the game. Stepping in place was also included to encourage light aerobic exercise, complementing the strength and coordination focus of the other movements. These movements were selected to balance feasibility and safety with engagement, while still aligning physical actions with cognitive decision-making.

The physical task is directly linked with the motion tracking implementation based on pose estimation models, as illustrated in Figure 2.2: from the body landmark coordinates, gesture recognition is performed, and once the movement is classified, it is translated into an input for game interaction. The input control will, in turn, define which object gets picked up, thus mirroring the choice in the cognitive task.

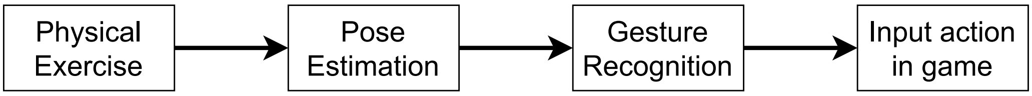


Figure 2.2: Overview of the input processing pipeline in the exergame.

Integration in Game Design

To integrate the previously discussed DT exercises, the exergame was designed as follows: the concept of recalling a sequence of items was translated into a gameplay scenario where the player navigates a fantasy-themed marketplace to collect objects as if from a grocery shopping list. The list of required items is displayed visually for a brief duration of five seconds, during which the player must memorise them before actually starting the level. Approaching the selling stands hosting the items requires moving forward in the environment, an action mapped to the stepping-in-place motion detected by the tracking algorithm. Once in front of the stands, the player is faced with a choice: picking the correct object from the list between two, placed either low on the ground or higher up on a shelf. The positioning defines the corresponding exercise needed to interact with it: a squat for the lower objects or an overhead press for the higher ones.

The DT is thus structured in accord with the previously discussed *Moving while Thinking* theory (see Section 1.3) [43]: solving the cognitive task and recalling which object ought to be collected comes before and hence becomes a requirement for the completion of the physical task. The user's avatar is blocked in place until a decision is made on which object to pick up, ensuring an effort is made in remembering the correct items.

Additionally, framing the visual episodic memory task as a grocery shopping list allows the activity to reflect IADL, which are often compromised in individuals with MCI. This alignment is intended to promote functional transfer, thereby improving both cognitive function and real-world independence [45, 47].

2.1.3 Feedback Mechanisms

As discussed in Section 1.2.3, feedback for older adults should rely primarily on audio and visual modalities rather than text. Building on these guidelines, the feedback system in this exergame was designed to integrate both real-time and post-session cues, ensuring clarity during gameplay and providing meaningful progress tracking afterward.

During gameplay, correct actions are reinforced with positive audio cues, while errors trigger distinct negative sounds, allowing players to immediately recognize their performance without interrupting the flow of the exercise. Visual clarity is enhanced through object animation: interactable items continuously bob and spin in place to indicate their relevance, and they disappear from the environment once collected, giving immediate confirmation of task completion.

In addition to real-time cues, the game provides a longer-term feedback layer. Scores from each session, along with completion times, are automatically recorded and made available on a dedicated statistics page. This dual approach balances continuous in-game guidance with post-session progress tracking, aiming to keep the player engaged in the moment while also fostering a sense of achievement and progression over time.

2.1.4 Digital Coach

As highlighted in the literature in Section 1.4, digital coaches (DC) can play a crucial role in exergames by fostering social presence, providing guidance, and motivating older adults to sustain engagement in training. Building on these insights, the exergame features an embodied DC, designed to act as a trusted friend rather than a distant expert. This choice reflects findings that older adults prefer relatable companions who embody perseverance and offer encouragement, rather than overly idealized athletic figures.

The coach's role is twofold: to guide the player through the exercises and to provide companionship throughout the experience, commenting on exercise performance, acknowledging correct actions and offering gentle suggestions for improvement when necessary. In addition, encouraging remarks are delivered at key moments, such as after item collection or subgoal completion, reinforcing the sense of achievement. In line with research recommendations, the DC's presence aims to combine practical guidance with motivational support, promoting confidence, social connection, and sustained adherence to training [53, 54].

2.2 End-User Focus Group Session

2.2.1 Preliminary User Feedback

In the context of the European project that provides the framework for this thesis, a focus group session was conducted between researchers and members of the target user population to gather co-design preliminary insights and opinions on various project features. Seven people participated in the meeting, four subjects with cognitive and/or cardiovascular disorders and three caregivers. They had the opportunity to view a video of an early version of the exergame, showcasing some of the game mechanics: the movement tracking to control interaction with the game, examples of the physical and cognitive tasks integrated with the game, along with audio-visual feedback mechanisms.

During preliminary consultations with the end users, several factors emerged as particularly important for ensuring engagement and usability. The idea of performing exercises using a tablet and movement tracking was understood and met with interest. Particularly appreciated was the possibility to have a portable solution and, by participants with cognitive issues, to perform cognitive tasks like ordering and remembering. Participants emphasized the need for a simple and accessible interface, supported by clear guidance from the research team, to make the system easy to approach. Integrability into daily routines was considered a key advantage: users would appreciate the possibility to perform exercises either standing or while seated and welcomed the idea of incorporating everyday objects (e.g., water bottles as weights) into training.

Motivation was seen to stem primarily from personal progression rather than competition. Participants highlighted that observing their own improvements over time, even when exercises became more challenging, was a strong stimulus. Conversely, competitive features such as leaderboards were often regarded as discouraging. For this reason, variety and gradual increases in difficulty were considered essential to maintain interest without overwhelming the player. Feedback was also considered valuable, but primarily in the form of constructive and individualized information about one's own performance, rather than external comparisons.

2.2.2 Impact on Exergame Design

These insights directly informed the design of the exergame. The system avoids competitive ranking mechanisms and instead focuses on personalized progression tracking through the statistics page.

This thesis prototypes a level of what would be a bigger game incorporating different kinds of tasks and DT exercises, so that a typical training session would require the completion of different, shorter levels with the market shopping being only one of them. This would allow for exercises to be adaptable in difficulty and flexible in execution, fitting into different contexts and user needs.

Moreover, shorter levels provide the user with the gratification of completing a task more often along with the possibility of reflecting on their performance, resting briefly, and reducing the strain connected with a much longer level that covers an entire training session.

Additionally, this approach responds to the patients need for "freedom" in choosing the preferred activities for a specific moment.

2.2.3 Impact on Digital Coach Design

The preliminary feedback on the concept of a digital coach strongly influenced the design of the companion in the exergame. Participants consistently preferred a human-like avatar over abstract or non-anthropomorphic figures, as it was perceived as more credible, relatable, and emotionally engaging. This led to the adoption of a human avatar for the coach, designed to act as a trusted friend rather than a distant or authoritarian instructor. The literature review had already emphasized the motivational benefits of social presence and peer-like role models, and this was confirmed in practice by user preferences for a reassuring and amicable companion.

The tone and personality of the coach were equally important: end users favored a calm, supportive, and collaborative style, with inclusive phrasing such as *"let's do this together"* rather than competitive or neutral messaging. This directly shaped the design of the coach's dialogue: the encouragements are spoken, offering audio feedback during exercises. While some participants appreciated the idea of a professional instructor, the broader consensus pointed to the value of a motivating teammate. To accommodate this, the coach's communication style was framed as empathetic, friendly, and positively reinforcing, aligning with older adults' preference for encouragement and recognition of personal progress rather than external competition.

Overall, the design of the coach combines the role of a supportive friend with the ability to guide exercises and comment on performance. By doing so, the coach is not only a functional feedback provider but also a motivational presence that enhances engagement and adherence to training.

Chapter 3

Project Architecture and Component Integration

3.1 Overall Architecture of the Exergame System

The Dual-Task Exergame was designed for mobile devices using an Android operating system. The tablet used to model and test the application is a Samsung Galaxy Tab S9 FE, a 10.9-inch Android tablet (Android 15, One UI 7). The device is equipped with an Exynos 1380 octa-core processor and 8 GB of RAM, providing sufficient resources to execute both a pose tracking model and the Unity-based exergame in real time. The frontal camera, a 12 MP ultra-wide sensor, is used to capture the user's full-body movements. Camera input is processed locally on the tablet, with the pose tracking model estimating body landmarks in parallel to the gesture classification. The Unity application runs concurrently on the same device, receiving motion data and translating it into in-game actions. This configuration allows for motion acquisition, processing, and gameplay to be integrated within a single portable device.

The design of the project brought forward the necessity of differentiating the concepts involved in modules to be implemented and then subsequently, integrated and tested. The main components are encased in two applications deployed to the device that work concurrently to constitute the Dual-Task exergame experience. They are illustrated in Figure 3.1, along with the main modules and features, and described as follows:

- **DT-Tracking:** responsible for the motion tracking, it receives the video feed from the tablet's front camera and identifies key points in the person's image, along with performing gesture recognition to identify the physical exercise completed by the user. These information are then sent through UDP protocol to the second application.

- **DT-Game:** developed with Unity game engine, it contains the actual exergame environment: the game levels are integrated in a interface from where the user is able to access the different features of the application. When accessing one of the levels, the user is prompted to complete a physical and cognitive task, with the Unity engine using the pose estimation data to define the player interaction with the game. The digital coach is developed in this environment, guiding the patient through the task.

The section 3.3 will explain in depth the structure of these two main components, along with the other smaller modules contained therein.

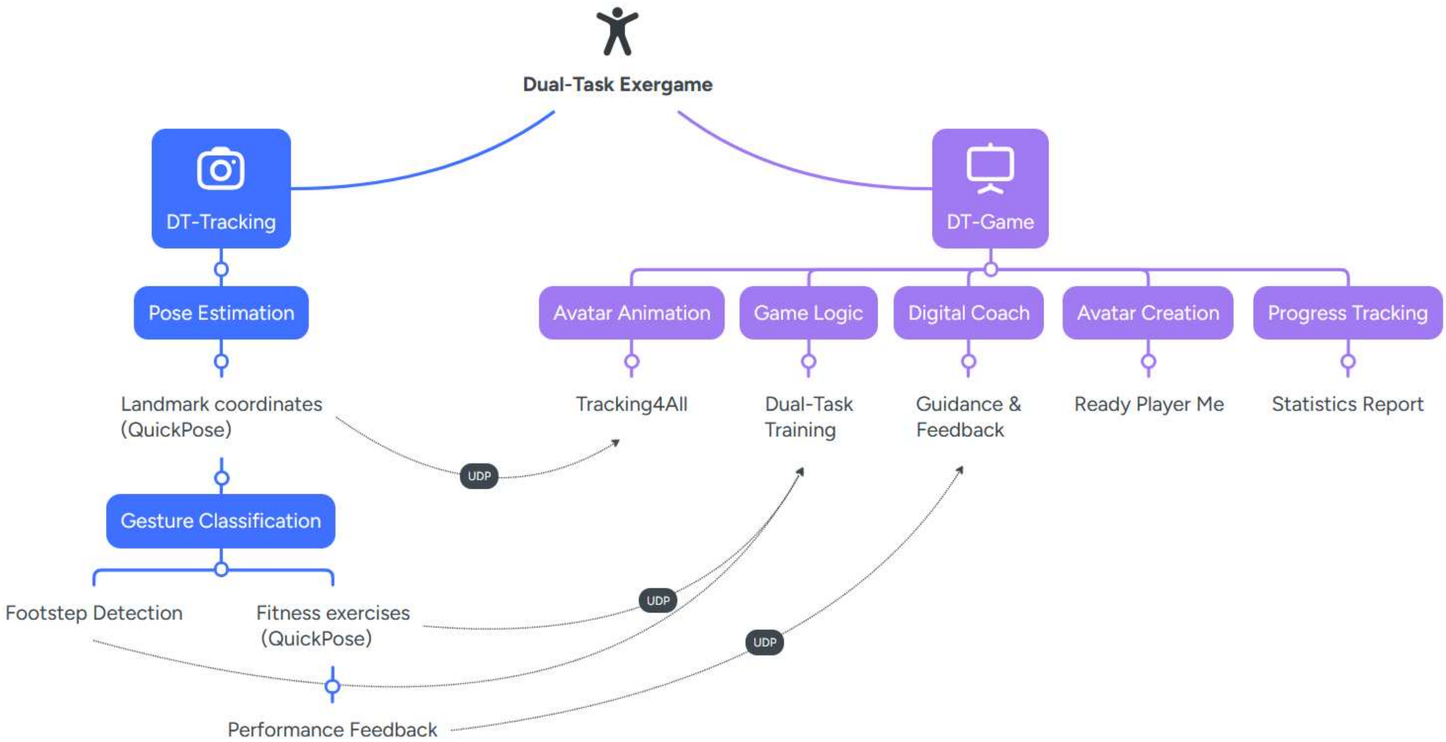


Figure 3.1: Overview of the system's architecture, illustrating the two main components, DT-Tracking and DT-Game, their features and the connection between modules.

3.2 Software and Tools

3.2.1 Unity Engine

The entirety of the DT-Game application was developed using the Unity Engine (version 2021.3.45f1 LTS). Unity provides cross-platform deployment, efficient mobile build performance, and straightforward integration of external Android plugins, which makes it suitable for running on a tablet device. Within this project, Unity was used to construct the game world, implement the avatar-based coaching interface, manage interaction logic, and deliver real-time feedback linking user motion data to in-game actions. To support the coach's avatar's verbal feedback, a Unity-compatible Text-To-Speech (TTS) plugin was integrated, enabling the coach character to provide spoken guidance and suggestions to the player [63]. Game mechanics for both the cognitive and physical tasks were prototyped and executed within Unity, ensuring real-time feedback and coherent integration with the motion-tracking components.

3.2.2 Ready Player Me

Ready Player Me (RPM) was integrated into the system as the primary tool for avatar creation [57]. Compatible with the Unity Engine, it provides a flexible WebView component that allows users to design their avatars directly from within the application, without manually accessing the website through the browser. Through this interface, players can select body type, hairstyle, clothing, and other visual features to create a personalized representation. In addition, the tool includes a selfie-based generation option, which captures a photo and automatically adapts the avatar's facial features to resemble the user. This functionality enhances the sense of embodiment and identification with the avatar, which is particularly important for older adults, as it strengthens engagement and the feeling of being guided by a familiar figure within the game world. The avatar generated through RPM is then seamlessly imported into Unity, where it is animated and used as the user's in-game character throughout the exergame experience.

3.2.3 QuickPose

QuickPose (QP) is a lightweight Android wrapper for Google's MediaPipe Pose solution [64]. It enables real-time estimation of 33 body landmarks from images captured by the tablet's frontal camera. In the context of this project, QP provides the motion-tracking backbone by running the pose estimation model locally on the device. This framework has been chosen to implement pose estimation in this project as it makes use of BlazePose's lightweight convolutional neural network, especially suited for real-time inference on mobile devices while also already implementing recognition for basic fitness movements [64, 65]. BlazePose is an approach to on-device body pose tracking developed by Google Research in the MediaPipe framework [66].

Figure 3.2 shows BlazePose's topology, with 33 landmarks used to reconstruct the user's skeleton. The model initiates pose estimation by detecting the user's face and inferring torso orientation and overall body alignment from that initial anchor. Moreover, after obtaining body landmark coordinates, the application subsequently implements gesture recognition of specific physical exercises. QuickPose's exercise library includes various fitness movements like squats, bicep curls, and lunges. The system analyzes joint angles and body posture to assess exercise performance and provide real-time feedback on the correct form to assume (e.g., *"lean upper body back"* during a squat).

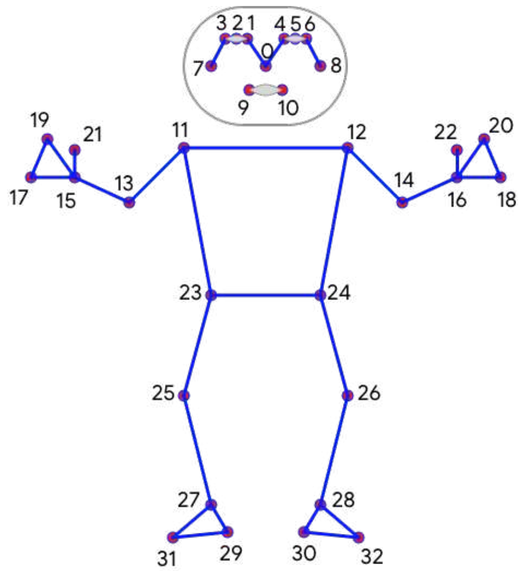


Figure 3.2: BlazePose's 33 keypoint topology [65].

3.2.4 Tracking4All

Tracking4All (T4A) is an Android plug-in for Unity that enables 3D avatar animation from webcam-based pose estimation models using a single RGB camera. It provides real-time estimation of body and hand movements, which can be applied to animate humanoid avatars within the game environment. The framework supports multiple operating systems, including Windows, macOS, Linux, iOS, and Android, and can be embedded directly in Unity applications. Within the system architecture, T4A constitutes the bridge between raw video input and avatar animation, processing the landmark coordinates obtained from a pose estimation model by means of an inverse kinematics algorithm and thus offering a solution for the translation of camera-based motion data into avatar animation, providing real-time visual feedback on the movements performed.

3.3 Exergame's Modules and Data Flow

3.3.1 DT-Tracking

The first of the two main components of this project is centered around the acquisition of the user's motion and its consequent tracking and classification.

As shown in Figure 3.1, the principal module of DT-Tracking is the one performing the pose estimation, constituted by the QuickPose framework. After the activation of the camera, the frame is processed as described in Section 3.2.3 and the body landmark coordinates are computed. Subsequently, the gesture classification module in QP identifies the motion completed by the user in the image and produces a string containing feedback on the exercise performance. Moreover, a custom algorithm was developed for footstep detection starting from the body keypoints data.

As a result, the output of the DT-Tracking application comprises landmark coordinates, gesture classification of the physical exercises, and the related performance feedback, all obtained through QuickPose, in addition to the step detection performed concurrently. The DT-Tracking is then linked to the second main component of the project, DT-Game, through a local UDP protocol as shown by the black arrows in Figure 3.1.

UDP Protocol

The data flows from DT-Tracking to DT-Game thanks to the implementation of a lightweight UDP-based protocol, over the local loopback interface (127.0.0.1), with DT-Tracking working as a client to the server ubicated in DT-Game. UDP offers low-latency communication suitable for continuous data streams, and its use ensures consistency with earlier cross-device testing where the Unity editor ran on a separate machine.

This design choice fits the two-application architecture with minimal overhead, maintaining a responsive gameplay experience and thus providing a pragmatic balance between performance and simplicity, and extensibility, while maintaining the option to later switch strategies if the applications are integrated into a single package.

3.3.2 DT-Game

The exergame environment is in turn composed of several modules, shown under DT-Game in Figure 3.1 and described in the following subsections.

Game Logic

The controls employed to interact with the game, in order to move forward through the environment or to pick up objects, are entirely a consequence of the information received through the UDP connection, as represented in Figure 3.3. The footsteps detected by the stepping algorithm are translated into the avatar advancing in the environment, while the classification of physical exercises defines which item will be collected. As a result of item collection, the inventory internal to the game gets updated, storing the number of objects correctly or incorrectly picked up; as illustrated in Figure 3.4, the statistics page in the menu retrieves these data from the inventory to display the corresponding performance charts.

Digital Coaching

As illustrated in Figure 3.3, two distinct feedback flows converge into the virtual coaching system, both ultimately voiced through the TTS plug-in. The first type, *performance feedback*, originates from QP, which detects incorrect postures or deviations during exercise execution. The corresponding feedback string is transmitted to the coaching module, which relays it verbally to the user in real time. The second type, *motivational feedback*, is generated internally by the *Game Logic* module, as shown in Figure 3.4, in response to gameplay events, such as correct or incorrect item collection. These messages serve to encourage the player and sustain engagement throughout the task.

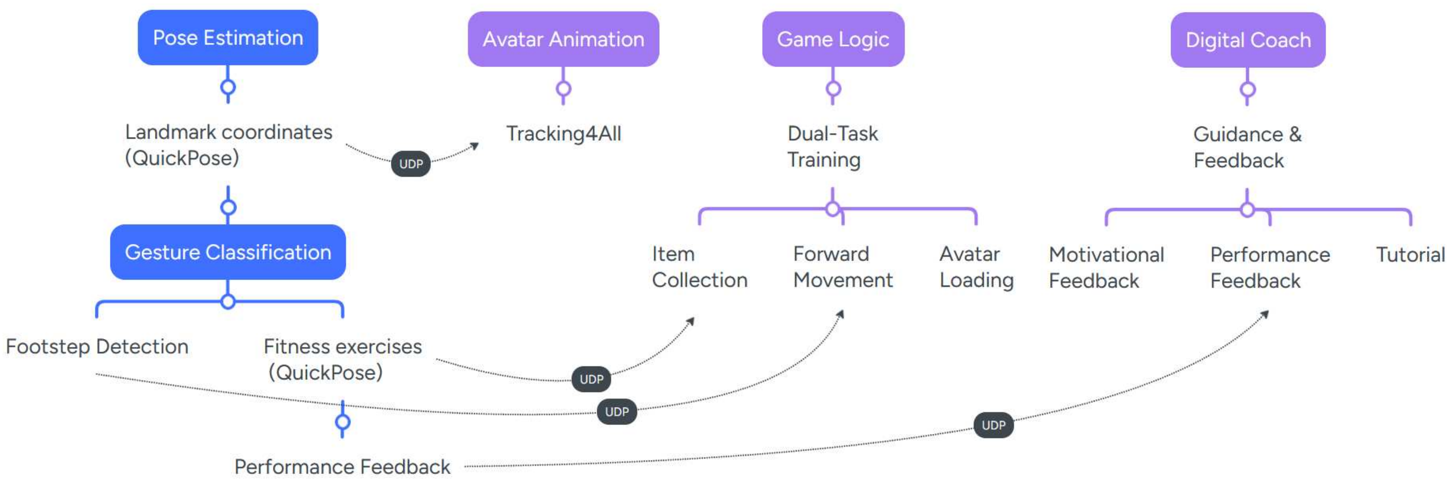


Figure 3.3: Inter-application communication between DT-Tracking and DT-Game via UDP over the local loopback interface. Pose and gesture data from DT-Tracking feed into gameplay, avatar animation, and coach feedback in DT-Game.

Avatar Creation

The module responsible for the avatar creation through RPM is accessed through a WebView component embedded in the application, where the player can create a personalized avatar before beginning the training. Figure 3.4 shows how, once created, the avatar URL identifier is exported and stored inside Unity in *PlayerPrefs*, a lightweight system to store small amounts of persistent data across game sessions, to be loaded once the user enters a game level. The RPM component functions as a preparatory stage, ensuring that the customized avatar is available to the Unity environment and ready for real-time animation during gameplay.

Avatar Animation

The raw landmark coordinates are received by the UDP server (Figure 3.3) and made available to the T4A's pipeline, driving the avatar animation process. The landmarks represent the main joints of the body and form the raw input describing the user's posture in real time. Filtering steps are applied to smooth the landmark trajectories and reduce noise. The processed coordinates are then converted into joint rotations to produce a consistent set of movement parameters for the 3D avatar inside the game environment, allowing players to see their movements mirrored in the virtual world.

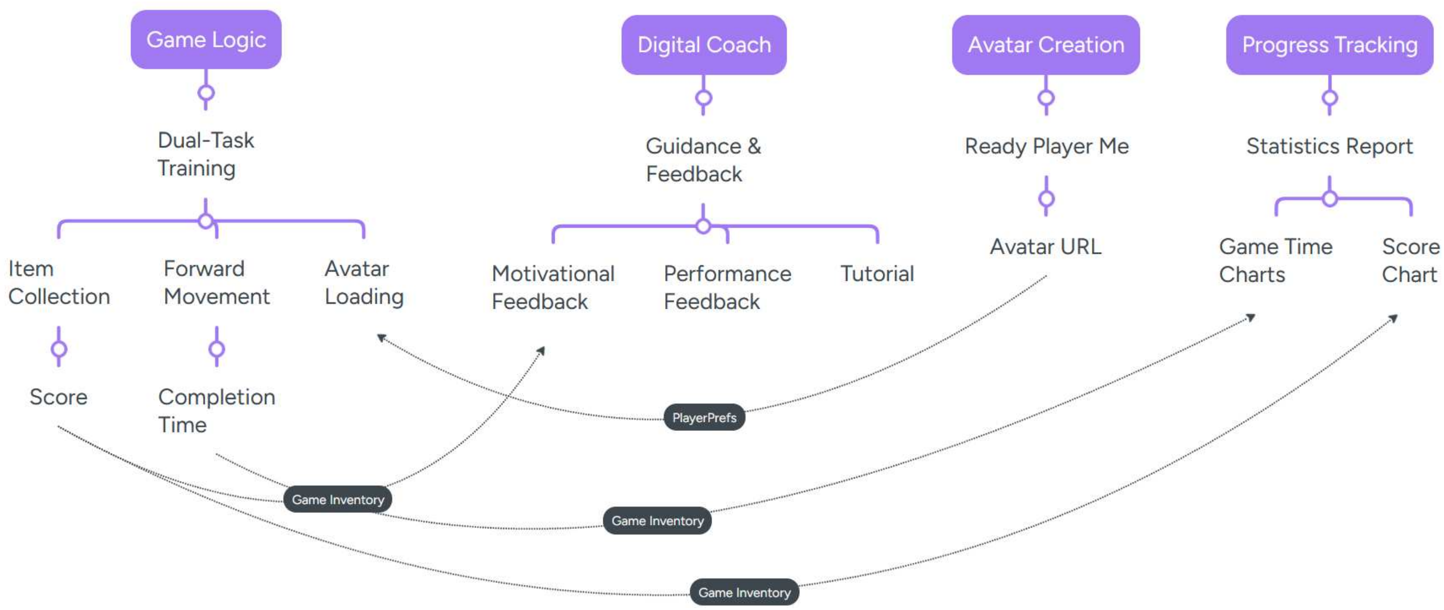


Figure 3.4: Intra-application architecture of DT-Game, showing data flow between core modules for gameplay, coaching, avatar management, and progress tracking.

Chapter 4

Implementation

In accordance with the structure presented in Chapter 3 at Figure 3.1, the following sections will detail the technical implementation of the two applications, DT-Tracking and DT-Game, along with their modules.

4.1 DT-Tracking

Developed in Android Studio, this application manages the units of the project related to the camera frames acquisition and processing. The treatment of the image is divided between user's movement tracking and fitness gesture recognition. The output data obtained by these two modules are then prepared to be sent to the application driving the exergame through a UDP protocol.

To allow the user to verify the correct functioning of the application, a screen overlay has been predisposed and is shown in Figure 4.1. This also enables the user to find a suitable position in the room to comfortably perform the movements while checking how they are viewed by the camera. A foreground service was then predisposed to enable the functioning of all the features even when the device focuses the DT-Game application instead, letting the tracking processes run in the background.

4.1.1 Pose Estimation

Quickpose (QP) is the framework implemented for pose estimation: after accessing the frontal camera of the tablet and gathering the image frames, the wrapper software employs BlazePose's model to detect the person in the image. As shown in Figure 4.1, the system can identify 33 body landmarks in real-time, providing 3D normalised coordinates within the camera reference system. The horizontal and vertical axes correspond to the normalized coordinates $x_n, y_n \in [0,1]$, respectively, where $x_n = 0$ and $y_n = 0$ represent the top-right corner of the camera frame with the tablet positioned vertically. The depth coordinate z_n is expressed as a relative value, with the reference point for $z_n = 0$ defined at the midpoint between the hips, and positive values increasing along the direction from the camera toward the user. The normalised keypoints are then treated with the following steps to obtain the landmarks in a consistent 3D coordinate system. First, pixel coordinates are computed as

$$x_p = x_n \cdot W, \qquad y_p = y_n \cdot H, \qquad z_p = z_n,$$

with W and H being the image width and height respectively. Next, the origin of the coordinate system is shifted to the hip center,

$$x_{\text{hip}} = \frac{x_{LH} + x_{RH}}{2} \cdot W, \quad y_{\text{hip}} = \frac{y_{LH} + y_{RH}}{2} \cdot H, \quad z_{\text{hip}} = \frac{z_{LH} + z_{RH}}{2},$$

where (LH, RH) denote left and right hip landmarks. Each landmark is then expressed relative to this origin and scaled into meters,

$$\Delta x = (x_p - x_{\text{hip}}) \cdot s, \quad \Delta y = (y_p - y_{\text{hip}}) \cdot s, \quad \Delta z = (z_p - z_{\text{hip}}),$$

where s is a pixel-to-meter scaling factor. This scaling factor s can be derived applying the camera intrinsic specifics: given a camera with sensor width S_w (in meters), and image width W (in pixels), the effective size of one pixel in meters is

$$s = \frac{S_w}{W}.$$

Given the focal length f and the Horizontal Field Of View (HFOV), the physical sensor width S_w can be obtained from the pinhole camera model as

$$S_w = 2f \cdot \tan\left(\tfrac{\text{HFOV}}{2}\right).$$

For the frontal camera of the Samsung Galaxy Tab S9 FE, the focal length is $f = 0.0017\,\text{m}$ and the horizontal field of view is $\text{HFOV} = 68.8°$, yielding

$$S_w = 2 \cdot 0.0017 \cdot \tan(34.4°) \approx 0.0023\,\text{m}.$$

Therefore, $s = 0.0023\,\text{m}$ is the scaling factor adopted in this project's implementation for converting pixel displacements into metric world coordinates.

Z-Correction

As the body keypoints are the core data used for avatar animation, further described in Section 4.2.2, it was necessary to implement an algorithm to improve the depth estimation performed by the underlying MediaPipe model in QP's framework due

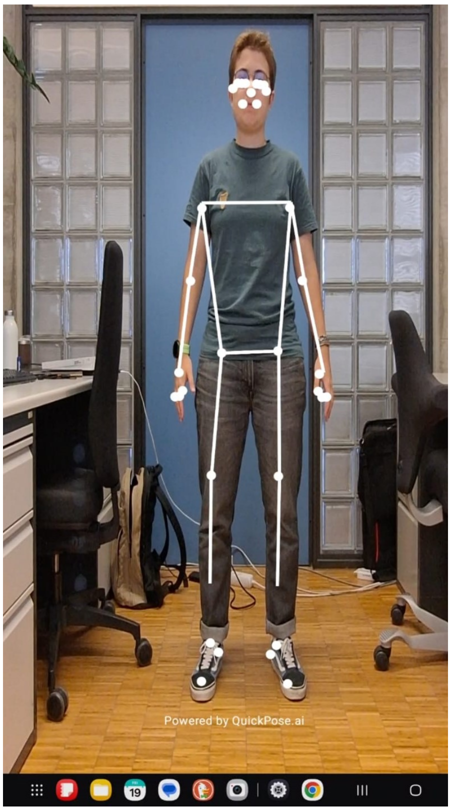


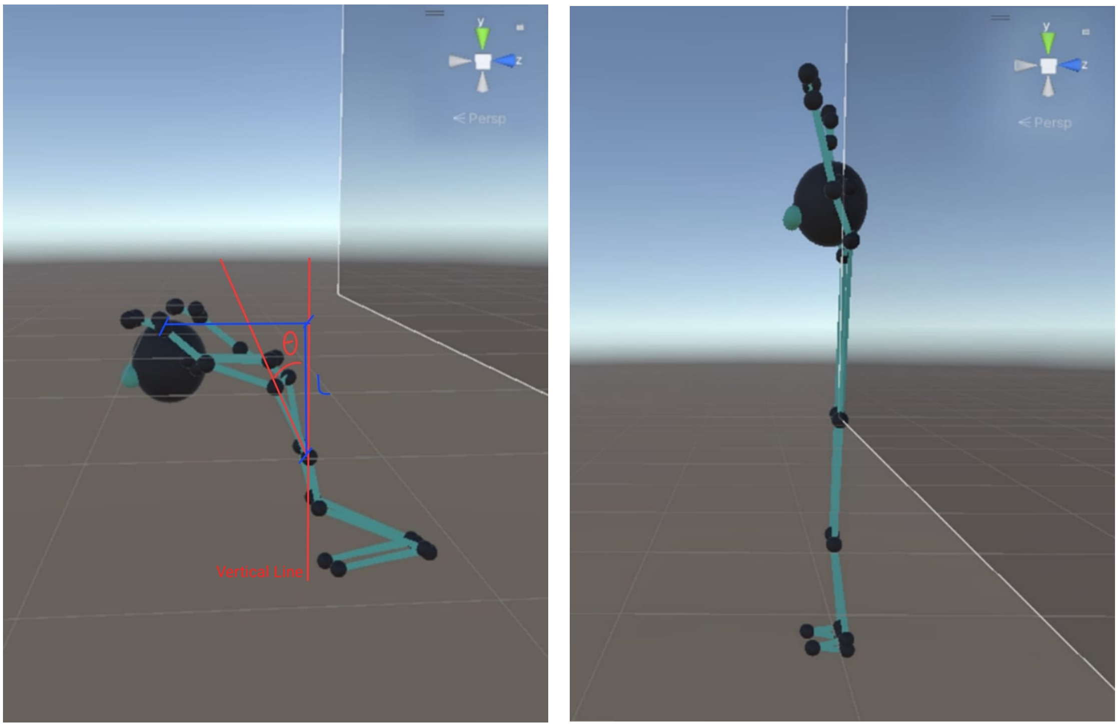
Figure 4.1: Graphic overlay generated by DT-Tracking, it shows the position of the 33 landmarks identified on the user by the pose estimation model, along with the skeleton connecting them.

to artifacts that heavily impacted the joint orientation computation needed to drive the avatar's 3D model animation. As described in [67], the 3D representation of the human posture is affected by different degrees of tilt based on the height at which the hands of the person stand in the image, as shown in Figure 4.2a, to be attributed to a lack of representation during the training of this model. Reproducing the approach outlined in [67], the z coordinate is corrected according to Equation 4.1.1 as the inclination of all joint points is consistent.

$$Z(Corrected) = \alpha(\theta, L) \cdot Z(Mdp) \tag{4.1}$$

In this formulation, Z(Mdp) denotes the depth estimated by the MediaPipe model, while Z(Corrected) represents the corrected depth value.

Hence, to compensate for the systematic tilt of MediaPipe's z predictions, the scaling coefficient $\alpha(\theta, L)$ is interpolated from an empirical correction matrix, where θ is the inclination angle of the torso and L is the hand height level relative to the hips.



(a) **(b)**

Figure 4.2: Example of the z-correction process applied to landmark coordinates. (a) Skeleton before correction, where inaccurate depth estimation causes tilt of the skeleton structure. (b) Skeleton after applying z-correction, with improved depth estimation and anatomically plausible alignment with the coronal plane.

At the end of this procedure, a hip-centered and tilt-corrected set of world coordinates is obtained, suitable for driving animation in a virtual avatar.

4.1.2 Gesture Recognition

The gesture recognition module is mostly managed by QP's framework: operating as a closed-source solution, it processes each incoming camera frame through a set of enabled features that include fitness movement classifiers, thereby allowing the simultaneous detection of a wide range of strength exercises. When one of the two chosen movements, squat and overhead press, is recognised, a dedicated exercise counter is updated. The count for each movement is then sent to DT-Game through the local UDP protocol, and will determine the action executed in the exergame.

Along with the fitness exercises, the stepping in place action is detected with a simple algorithm constructed outside of QP. The step detection algorithm relies on monitoring the relative position of the hips and knees to identify lifting movements of the legs. A step is recognized when the distance between hip and knee decreases beyond the 90% of said distance, indicating that one leg is being raised, and the event is confirmed and classified once the leg returns to its initial extension. To avoid fixed thresholds that would be unreliable across different users, postures and positioning in front of the camera, the method employs a dynamic reference: a "stable stance" baseline for the hip-knee distance is periodically updated whenever the subject is standing in a balanced position. This reference allows for adapted thresholds and the reliable detection of stepping motions in changing conditions.

The detection of a stable stance follows four main rules:

- **Feet alignment:** Both feet must be at approximately the same level with respect to the ground.
- **Knees alignment:** Both knees must also be roughly at the same level.
- **Upright legs:** The legs should remain nearly vertical.
- **Step inactivity:** No active stepping motion should currently be in progress.

In addition, the algorithm integrates a timeout and reset mechanism to improve robustness and account for sudden movements of the user in the camera FOV, that may invalidate the threshold computed in a given position. If a step remains active, because the hip–knee distance has not yet returned to its resting threshold, for longer than a maximum duration (e.g., $2s$), the system automatically resets the state and awaits a new stable stance reference.

In conclusion, the step count is also added to the information sent to DT-Game, and will be used to determine the forward movement of the avatar.

4.1.3 UDP Protocol

For the communication layer in the double-application setup, a lightweight local UDP protocol was adopted. The DT-Tracking Android application acts as the client, continuously streaming motion-related information, that include:

- Fitness exercise counters.
- Footstep counters.
- Treated landmark coordinates.
- Textual exercise performance feedback.

On the other end, the DT-Game Unity application operates as the server, receiving and processing this data in real time. The transmitted payloads are structured as JSON objects, which provide a flexible and modular representation: the format can be easily extended or reorganized if the data structure evolves, without requiring substantial changes to the communication logic.

4.2 DT-Game

The DT-Game application contains the implementation of the actual exergame, and it presents itself with the traditional appearance of mobile game. Figure 4.3 shows the *Main Menu*, the first interface the user encounters: the four simple buttons showcase the features of the application, the *Settings*, visible in the down-right corner, the *Statistics* page from which to monitor long-term progress, the *Create Avatar* section, discussed in Section 4.2.1, and finally the *Start* button, that enables access to the game levels. Figure 4.4 complements Figure 4.3 by detailing the user interaction flow with an activity diagram, outlining how each *Main Menu* option leads to the corresponding features.

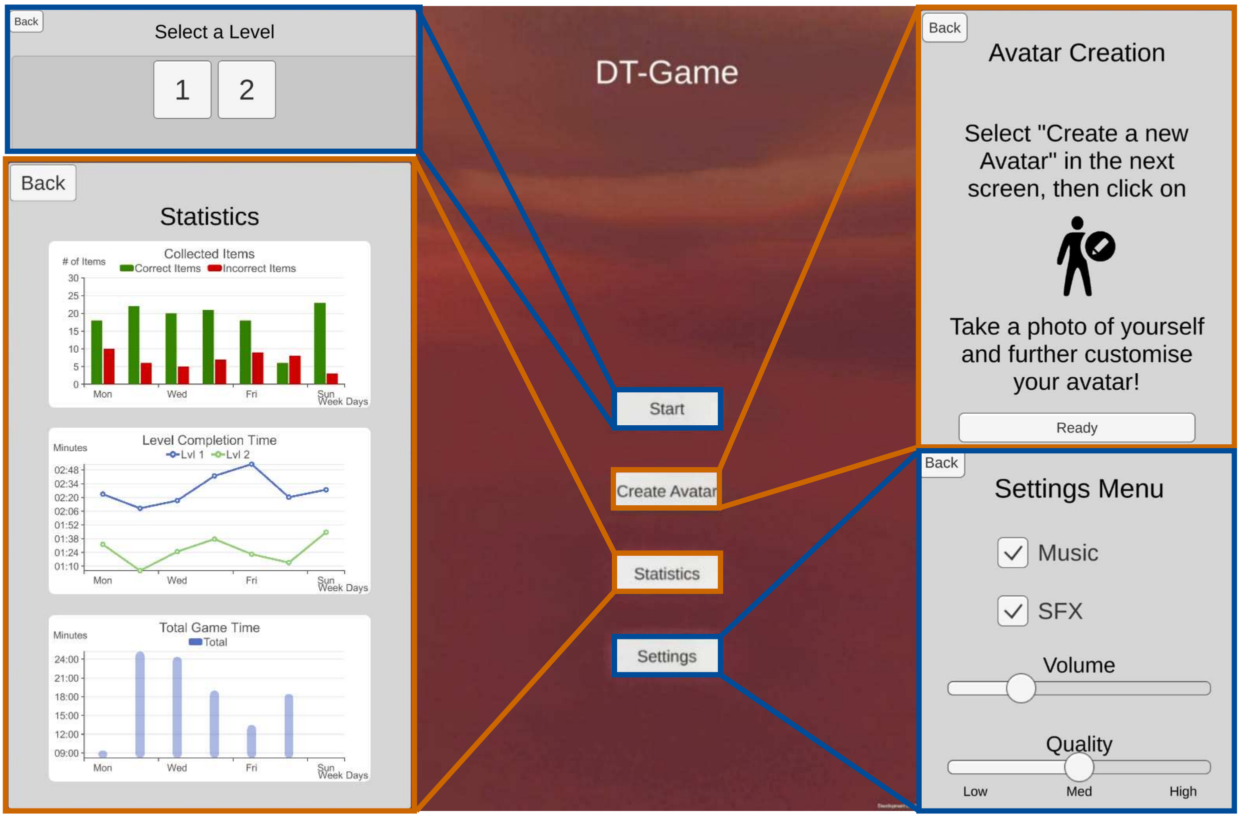


Figure 4.3: Overview of the DT-Game main menu and its related interfaces. From the central screen, users can access four subsequent interfaces corresponding to the main options: *Level Selection*, *Statistics*, *Avatar Creation*, and *Settings*. Each panel illustrates the interface displayed upon selecting the respective button from the main menu.

The complete swimlane diagrams for the *Avatar Creation* and *Exergame Level* activities are provided in Appendices A and B, respectively.

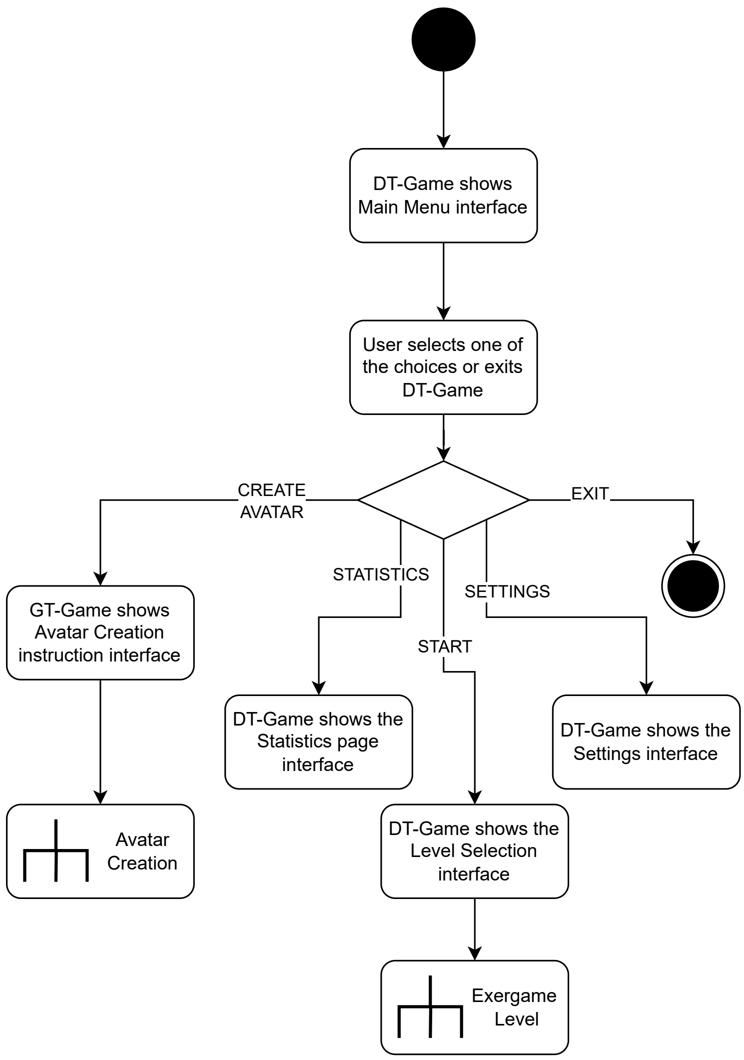
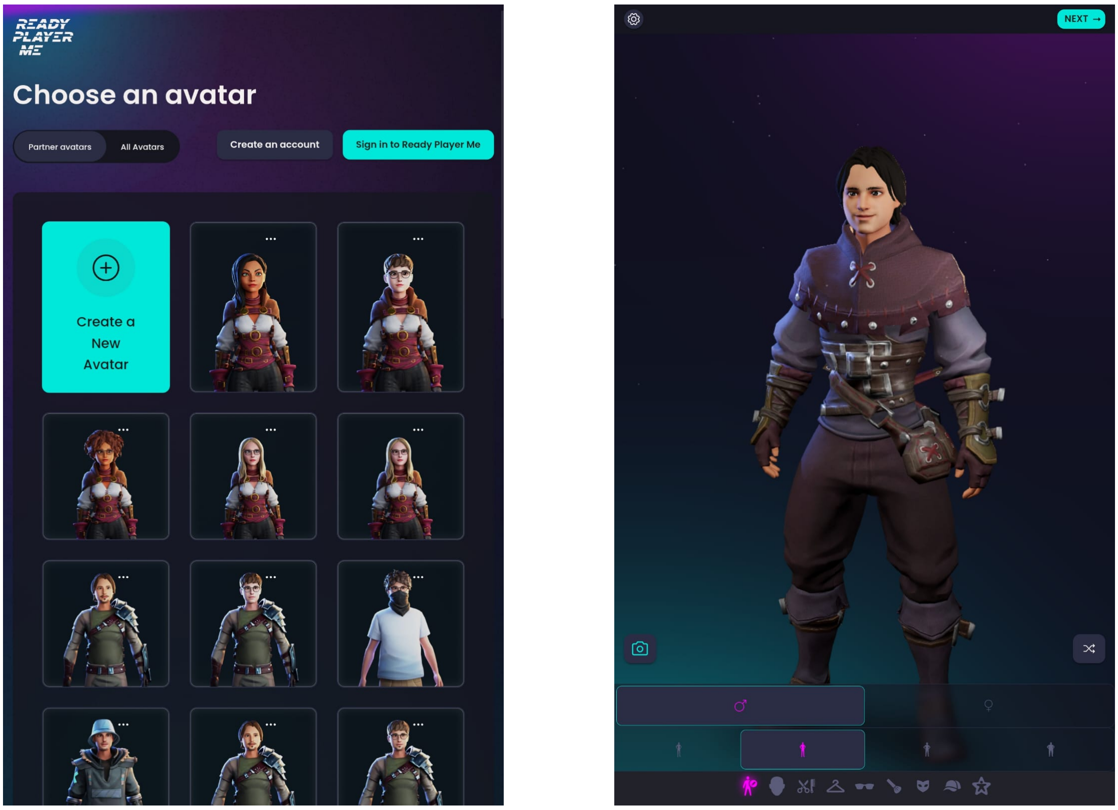


Figure 4.4: Activity diagram with the navigation flow of the DT-Game application. Starting from the *Main Menu*, the user can access four primary features, *Avatar Creation*, *Statistics*, *Settings*, and *Level Selection*, or exit the game. The *Avatar Creation* and *Exergame Level* activities are described in more detail in Appendices A and B.

4.2.1 Avatar Creation

When entering the *Create Avatar* page, the user is first faced with some brief instructions on what to do to generate a new avatar, ensuring autonomy in this process every time the user decides to change their embodiment in the game. The Webview component then redirects the user to the Ready Player Me (RPM) interface for avatar creation, shown in Figure 4.5a. In the subsequent page, represented in Figure 4.5b, the user can customise the avatar's appearance to their preference, with the option to capture a photo of their face. In this case, RPM's artificial intelligence automatically generates an avatar with features resembling the user's. By choosing the photo option, users implicitly consent to the processing of their image data by the RPM service.



(a) (b)

Figure 4.5: (a) Ready Player Me (RPM) avatar selection interface: users can create and store multiple avatars, choosing among them at will.(b) Avatar customisation interface: upon selecting *Create a New Avatar*, RPM generates a random avatar that can be freely customised using the icons at the bottom of the screen or by taking a photo of themselves and generating an avatar with similar features.

Once the avatar has been finalized and the user presses the *Next* button on the upper part of the screen in Figure 4.5b, the model is associated with a unique URL identifier provided by the RPM platform and saved in *PlayerPrefs*, a lightweight system to store small amounts of persistent data across game sessions. This URL link points to the cloud-hosted 3D model of the avatar and ensures that any changes made by the user through the RPM interface are automatically reflected in the avatar when this is retrieved and loaded inside a game level. This solution forces the user to have a functioning internet connection and to wait a few seconds for the avatar to load. However, it allows the patient to create a new avatar or to choose a different one for each session while not weighing down on the system, as the various avatar models are not downloaded and stored locally on the device.

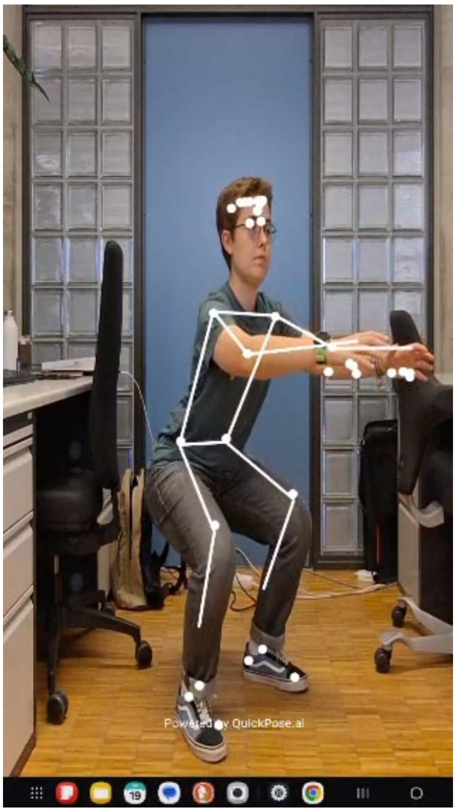
4.2.2 Avatar Animation

To further heighten the patient's sense of presence and immersion in the game, the decision was made to have the avatar replicate the movements of the user by means of the Tracking4All (T4A) forward kinematics algorithm presented in Section 3.2.4. Starting from the body landmark coordinates received via UDP, T4A implements filtering steps to smooth the data. The pre-processed coordinates are then transformed into joint rotations by means of an inverse kinematics algorithm : each couple of landmarks defining a joint of the 3D model of the avatar is used to compute orientations of said joints in the virtual space, resulting in the real-time animation of the avatar model according to the pose assumed by the user.

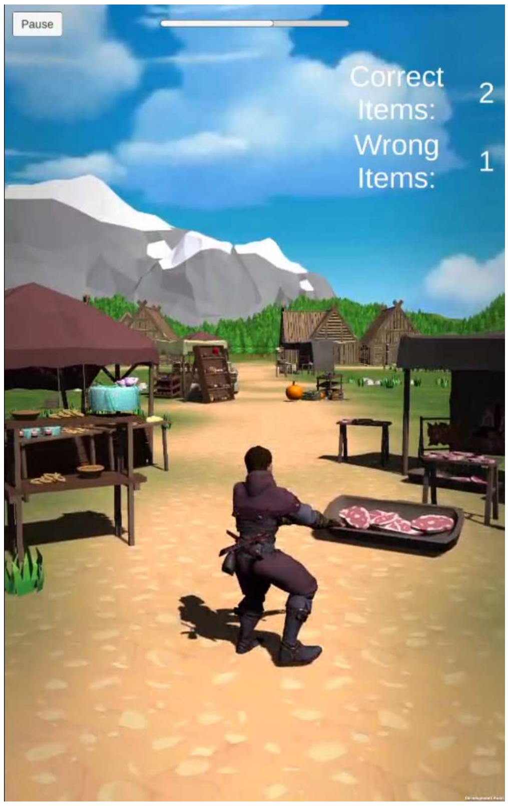
This tool allows the player to have direct visual feedback of the physical exercises they are performing, having their avatar move exactly like them, and not only interacting with the game world in light of the action performed. Figure 4.6a shows a user in the process of performing a squat, while in Figure 4.6b the avatar in-game portrays the exact same movement in real time.

4.2.3 Exergame Level

At the start of the level implemented in this thesis, the user's avatar is loaded in the game environment, a market situated in a fantasy setting, along with the digital coach's avatar that welcomes them and explains the task and the movements to perform through a brief tutorial with the help of the TTS tool: the player will have to walk through the market raising their knees, collecting a list of items; the objects positioned low on the ground can be collected by completing a *squat*, while the items placed high on a shelf have to be retrieved through an *overhead press*. This exergame level is implemented akin to a *runner game*, a genre of mobile videogames characterised by continuous forward motion of the player's character through a simple environment, where interaction is limited to a small set of controls and



(a)



(b)

Figure 4.6: Comparison between the physical execution of a squat by the user (a) and the corresponding replication of the movement by the virtual avatar embodiment (b).

challenge and engagement arise from timing, coordination, and sustained attention rather than complex input schemes. Figure 4.7a shows the moment in which the list of objects, composed of vegetables, fruit, and other types of food, is shown to the patient, who then has to collect them throughout the game, performing the visual episodic memory task by recalling and recognising them.

The interaction with the game takes place entirely through the actions performed by the user in front of the camera: the avatar is driven forward when the stepping motion is recognised in DT-Tracking from the user walking in place; as long as the step count received through the UDP protocol continues to increase, the avatar moves forward. Similarly, the item collection is driven by QP's recognition of the two physical exercises. Throughout the level, the patient is repeatedly confronted with having to make a choice between two items, as exemplified in Figure 4.7b: only one object corresponds to the shopping list shown at the start of the level. When the avatar reaches the objects, a method was implemented to stop the avatar and not allow further progress in the game world until one of the two fitness movements is performed, thus collecting an object, in line with the *Moving while Thinking* theory [43].

(a) **(b)**

Figure 4.7: a) The coach (right) talks to the patient's avatar, greeting them and explaining the task. The frame depicted shows the list of items to be collected in this game level. b) The user has advanced in the level and faces the first item collection choice. In the picture, the market environment is visible, with some food stands visible on both sides of the path.

Feedback Mechanisms

Visual "juicy" feedback elements were added, making the collectible items spin and bob in place, which also helped make them more easily identifiable in the midst of the other market items. After making a choice and collecting one of the two options, the game casts a Unity event, triggering a series of actions related to item collection: a sound effect, either positive or negative, is respectively associated with a correct or incorrect retrieval. These cues offer immediate feedback to the users on their choice and further add a layer of "juiciness" to the interaction. Moreover, the current score of the user, visible in the upper right corner of the screen in Figure 4.7b gets updated, and the digital coach remarks with an encouraging sentence on the accuracy of the choice.

In the game environment, a starting and finish line are also present, to signal the user of the incoming completion of the level. For the same purpose, a dynamic bar is added to the top of the screen (visible in Figure 4.6b): it gives immediate feedback to the user on the level completion progress by filling up in relation to the amount of space covered by the avatar.

At the end of the level, a performance overlay like the one shown in Figure 4.8a is presented to the player, offering a concise summary of overall results. This interface provides aggregate feedback by reporting the number of correct and incorrect items, the time taken to complete the task, and progress in terms of experience points (XP). The completion of a level is equivalent to a certain amount of XP, and the partly filled bar visible in Figure 4.8a reflects the possibility of gaining more XP by completing more levels in the same exergame session. The inclusion of a star-based rating system delivers an easily interpretable evaluation of success, reinforcing achievement while encouraging continued engagement and improvement across sessions.

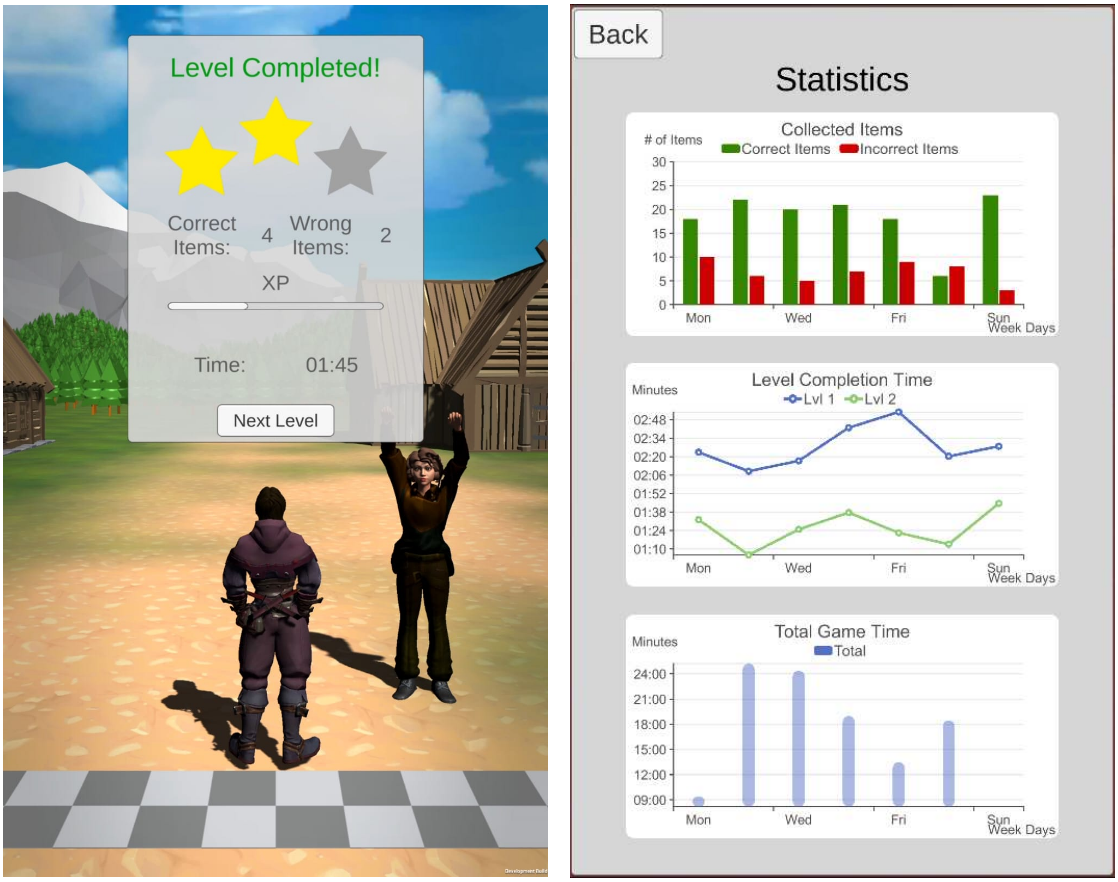
Digital Coach

The coach is represented in the game with a female avatar, greeting the user with friendly words and gestures, explaining the task, as visible in Figure 4.7a, and simulating the movements to perform. The TTS plug-in used to give voice to the coach is based on a Java bridge class, acting as an interface between the default Samsung text-to-speech engine and Unity's C# environment. The bridge passes parameters (e.g., language, prompt, pitch, and rate) from Unity to Android, configures the services, and starts/stops speech as needed.

The digital coach is present with its physical representation at the start of the level to deliver the tutorial and then reappears again at the end of the level, to congratulate the player and offer support in case the patient didn't perform optimally. During the course of the level, the coach doesn't contribute in its embodied form but comments assiduously on the performance of the user, through the use of the TTS generated voice.

From DT-Tracking, feedback is received in the form of a string of text both about the fitness form (e.g., *"Lean upper body back"* during a squat) and on the suitability of the user position in front of the camera (e.g., *"Stand facing camera"*). Conversely, the motivational remarks are chosen among a set of sentences based on user accuracy in the cognitive task: in case of collection of the incorrect item, a supportive message is spoken (e.g., *"That was a tricky one — let's try again together."*); while encouragements are delivered for consecutive recollection of the correct objects (e.g., *"You remembered perfectly — that's sharp thinking!"*).

Similarly, after level completion, the coach remarks with different levels of celebratory and motivating statements to reflect the accuracy achieved during the level: the coach always congratulates the user on completing the task, and then adds a comment ranging from *"This task was challenging, but each try builds your skills."* with zero stars achieved in the final progress overlay, to *"Excellent work — you completed everything perfectly!"* in case the maximum score was achieved.



(a) (b)

Figure 4.8: a) Example of the end-of-level performance summary overlay, showing accuracy, experience points, and completion time. In the background, the coach cheers for the successful level completion. b) *Statistics page*: the upper chart shows daily totals of correctly and incorrectly collected items, while the two lower charts display respectively average completion time per level, and time spent in the exergame.

4.2.4 Progress Monitoring

As a last feature of the DT-Game application, from the *Main Menu* the user has access to the *Statistics* page, allowing them to reflect on their progress and review their performance after each exergame session. Displayed in Figure 4.8b, the first chart presents the number of correct and incorrect items recalled in the visual episodic memory task during an entire session, thus aggregated by day. The second chart illustrates the average time taken to complete each level, while in the third chart is represented the total time spent in the exergame per day. While an increase in total playtime may reflect greater adherence and engagement, a decrease in average level completion time can be interpreted as an indicator of improved efficiency and proficiency in executing the dual-task, encompassing both physical and cognitive components.

This visualization supports users in tracking their cognitive accuracy and exercise engagement over time.

Chapter 5

Testing Methodology

The previous chapters have delineated the design, architecture and implementation of the Dual-Task exergame for people at risk of Mild Cognitive Impairment (MCI). A testing phase was therefore predisposed to evaluate the prototype: the goal of this early testing was not to validate the system with the intended end-users, but rather to involve a younger convenience sample with varied educational and professional backgrounds, in order to identify technical issues and assess usability.

In addition, a preliminary evaluation was conducted on more specific features pertaining to the project, like immersion, presence, and user perceived competence during play.

5.1 Procedure

Participation was voluntary and based on the written informed consent available in Appendix C. Participants were informed about the study's objectives, procedures, and data protection guarantees, in line with the Swiss Federal Data Protection Act (RS 235.1).

Before starting the session, participants completed a questionnaire on their background, further discussed in (Table 5.1). They were then introduced to the exergame and its context (Appendix D), to have them familiarise with the game world and its objective. The user was guided in the avatar creation part, ensuring the generation of a representative avatar in accordance with their preference, as shown in Figure 5.1a. Simulating a first onboarding session in which the patients would adjust to the movement tracking function, the users were directed in the initial interaction with the DT-Tracking application.

During the test session, a moment of which is depicted in Figure 5.1b, participants engaged with the exergame while their performance and interactions were observed. Each participant was asked to repeat the task twice, completing two levels that were structurally identical except for the specific list of objects to be collected. Afterward, they were asked to complete a questionnaire on their experience, described in more detail in Section 5.2, and reported both in Table 5.2 and in Appendix E. Additionally, a brief interview was conducted to determine specific feedback on the most immersive feature of the exergame, the fluidity of the user interaction, and potential confusion points encountered during the experience. The users also had the possibility to provide further feedback on bugs, difficulties, or to make other remarks on the experience.

(a) (b)

Figure 5.1: Pictures from the testing phase. (a) A user customises the avatar after having generated it from a picture. (b) A user performs an overhead press during the testing of the exergame level.

5.2 Questionnaires and metrics

Given the user-oriented nature of the project, it was fitting to focus on user experience and satisfaction during the testing of the first prototype of the exergame. Understanding user experience provides useful insights for the future development of more enjoyable exergames and thus, more specifically to the case at hand, to the increase of intervention adherence in the context of prevention and rehabilitation.

In general, the testing of user experience in exergames can draw from different methodologies [68]:

- **Objective measuring:** Physiological measures like heart and respiration rate, electromyography, electroencephalography and electrodermal activity are commonly employed. While offering objective data, these methods are costly and difficult to interpret; even when adding analytics derived from in-game behaviours, complexity remains high and there is still uncertainty on their relashionship with actual subjective experience.

- **Subjective measuring:** Interviews and questionnaires are more affordable with the latter also being easily distributable on a larger scale. They permit to focus on specific aspects of the experience, some of them being developed to inquire on satisfaction and enjoyment, challenge and immersion [30, 69, 70, 71].

When working with the intended users of the application, it might also be of interest to construct a questionnaire based on *Technology Acceptance Model* theory [72]: according to this framework, users tend to accept or reject the use of digital tools based on their *perceived usefulness* and *ease of use*, which in turn will modulate the *attitude* and *behavioural intention* to use the proposed application.

While the recruitment of the target population (older users at risk of MCI) was not feasible at this stage, a younger demographic was involved to assess usability and aspects of the design: the System Usability Scale (SUS) was chosen as a well-validated and widely employed questionnaire for user experience [73, 74, 75].

Moreover, the Player Experience of Needs Satisfaction (PENS) [30] was explored and part of it, items 11 to 16 in Table 5.2, was used to obtain a first impression on motivational aspects like competence and presence in-game.

Finally, to inquire on specific aspects that can impact the embodiment illusion, such as *external appearance* and *location of the body*, a subset of questions was extrapolated from the Avatar Embodiment questionnaire (items 17 to 19 in Table 5.2) [70].

Background Information

To collect demographic information and understand participants' background, a short questionnaire was administered (Table 5.1). This section includes items on age, gender, education, and field of work or study, as well as self-reported gaming habits, familiarity with motion-based games, and physical activity levels. These questions provide contextual information for interpreting participants' experiences and performance in the study.

#	Item	Response
	Demographics	
1	Age	18–25 26–35 36–45 46–59 60+ Prefer not to say
2	Gender	Female Male Non-binary Other Prefer not to say
3	What is the highest level of education you achieved?	No formal education Compulsory High School Bachelor's Master's Doctorate Other
4	What is your field of work/study?	Open response
	Gaming habits	**Response**
5	How often do you play video games?	1 2 3 4 5
6	How familiar are you with motion-based games?	1 2 3 4 5
7	How physically active are you in daily life?	1 2 3 4 5

Table 5.1: Demographic and background questionnaire items. The first section (Items 1–4) collects demographic information on age, gender, education, and field of work/study. The second section (Items 5–7) captures participants' gaming habits, familiarity with motion-based games, and physical activity levels.

System Usability Scale (SUS)

The SUS is a well-established questionnaire originally designed in 1996 to measure the perceived usability of interactive systems. Its 10 items are visible in the first section of the questionnaire at Table 5.2 and the responses are given on a 5-point Likert scale ranging from Strongly disagree to Strongly agree. The score is converted into a value between 0 and 100, where higher scores indicate better usability, with 68 generally considered as the threshold between acceptable and poor usability.

The SUS explores three aspects of user experience:

1. **Effectiveness:** the user's ability to achieve their goals and complete their tasks;
2. **Efficiency:** the effort and resources required to achieve those goals;
3. **Satisfaction:** the user's subjective evaluation of the experience.

It was decided to use the complete version of the questionnaire, as only the sum of the 10 ratings can be confidently regarded as a general measure of perceived usability.

The SUS is employable with reliable results even with small sample sizes (8-12 people) [74, 75] and it is also designed for quick administration, to minimize participant burden after the use of the application. In an effort to maintain this criterion, only 10 items are added to the proposed questionnaire, with the objective of also evaluating the design features aimed at promoting user immersion and engagement towards the exergame.

Player Experience of Needs Satisfaction

The PENS questionnaire evaluates the extent to which a game satisfies three psychological needs identified by Self-Determination Theory [30]: competence, autonomy and relatedness. Furthermore, the PENS also includes subscales to assess presence and intuitiveness of controls. Items include statements such as "*I felt capable and effective while playing*" (competence) or "*Exploring the game world feels like taking an actual trip to a new place*" (presence), rated on a 7-point Likert scale.

PENS, was selected as a complementary measure to SUS, focusing on motivational and experiential aspects that are especially relevant for exergame design. The six questions extrapolated from the original PENS questionnaire, that is present in its entirety in Appendix F, are reported in Table 5.2 (see items 11-16), and were chosen to evaluate the following aspects:

1. **Competence:** This refers to the need for challenge and feelings of effectiveness or accomplishment while playing the game.

2. **Presence:** A sense of immersion in the game world, feeling as if one is within it rather than outside, manipulating controls.

3. **Intuitiveness of controls:** The degree to which game controls are user-friendly, easily mastered, and do not interfere with the sense of being in the game.

Avatar Embodiment

The remaining items of the proposed questionnaire were taken from the Avatar Embodiment questionnaire (see Appendix G) presented by [70], which integrates validated survey items on immersion and embodiment in virtual environments from a variety of previous studies. Of particular interest are the questions regarding the *location of the body*: since the Dual-Task exergame employs a third-person perspective, the embodiment illusion requires the player to identify with a virtual body positioned in a different location in space. Furthermore, questions regarding the avatar *external appearance* were added to collect feedback on the degree of identification with the avatar, which in this case is designed to be a look-alike of the user.

Together, SUS and PENS allow the evaluation to capture both the practical usability of the exergame prototype and its ability to promote engaging player experiences. The use of these two instruments, along with the avatar embodiment evaluation, ensures that even in an alpha phase with a non-representative population, valuable insights can be obtained to guide subsequent development and testing with the target demographic.

Qualitative Feedback (Interviews)

In addition to the questionnaire, participants were asked three open-ended questions aimed at capturing qualitative impressions of the experience:

1. *"What was the most immersive feature?"*
2. *"What part of the experience felt the most awkward or not smooth?"*
3. *"What were points of confusion that you wish had been explained better?"*

These questions were designed to complement the quantitative results by highlighting specific aspects of immersion, interaction fluidity, and clarity of instructions that shaped participants' perceptions of the exergame. Participants were also invited to provide any additional comments, including remarks on bugs, difficulties, or other aspects they felt relevant.

Completion time and score

For each of the two levels completed by the participants, data were collected on the time required to finish the task as well as on performance accuracy, measured in terms of correctly and incorrectly collected objects. These measures were selected to assess both efficiency (time to completion) and effectiveness (accuracy of object collection) in performing the exergame tasks. By comparing results across the two levels, it was possible to evaluate differences in performance and potential improvements in usability associated with repeated use.

#	Item	Response						
	System Usability Scale (SUS) items	***Strongly disagree***				***Strongly agree***		
1	I think that I would like to use the exergame frequently.	1	2	3	4	5		
2	I found the exergame unnecessarily complex.	1	2	3	4	5		
3	I thought the exergame was easy to use.	1	2	3	4	5		
4	I think that I would need the support of a technical person to be able to use the exergame.	1	2	3	4	5		
5	I found the various functions in the exergame were well integrated.	1	2	3	4	5		
6	I thought there was too much inconsistency in the exergame.	1	2	3	4	5		
7	I would imagine that most people would learn to use the exergame very quickly.	1	2	3	4	5		
8	I found the exergame very awkward to use.	1	2	3	4	5		
9	I felt very confident using the exergame.	1	2	3	4	5		
10	I needed to learn a lot of things before I could get going with the exergame.	1	2	3	4	5		
	Player Experience of Needs Satisfaction (PENS) items	***Do Not Agree***						***Strongly agree***
11	I feel competent at the game.	1	2	3	4	5	6	7
12	The game controls are intuitive.	1	2	3	4	5	6	7
13	When I wanted to do something in the game, it was easy to remember the corresponding control.	1	2	3	4	5	6	7
14	When playing the game, I feel transported to another time and place.	1	2	3	4	5	6	7
15	When moving through the game world I feel as if I am actually there.	1	2	3	4	5	6	7
16	When I accomplished something in the game I experienced genuine pride.	1	2	3	4	5	6	7
	Avatar Embodiment items	***Do Not Agree***						***Strongly agree***
17	It felt as if my (real) body were turning into an 'avatar'.	1	2	3	4	5	6	7
18	At some point it felt that the virtual body resembled my own (real) body, in terms of shape, skin tone or other visual features.	1	2	3	4	5	6	7
19	I felt as if my body was located where I saw the virtual body.	1	2	3	4	5	6	7

Table 5.2: Questionnaire employed in the *alpha testing*. SUS items (1–10) use a 5-point Likert scale, while PENS (11–16) and Avatar Embodiment (17–19) items use a 7-point Likert scale.

Chapter 6

Testing Results

6.1 Participants

A total of $N = 27$ participants took part in the alpha testing. Recruitment followed a convenience sampling approach within a university context. The majority of the participants fell in the 18–35 age range, with just 2 persons aged between 36 and 45, and one person between 46 and 59. In terms of gender distribution, 44.4% identified as female, 55.6% as male.

The sample was highly educated, reporting at least a high school level of education. Among them, 70.3% had completed a bachelor or master university degree, and 18.5% held a PhD. Participants' field of study or work included computer science, physics, biochemistry, biomedical and electronic engineering, education, psychology, digital marketing, insurances, mechanics and sports science.

The participants reported relatively low to moderate gaming experience, with 33.3% indicating that they never play (rating 1 on a 5-point scale) and only a small minority (3.7%) describing themselves as daily players (rating 5/5). Similarly, familiarity with motion-based games was limited, with the largest proportion of participants (37%) declaring no prior experience (rating 1/5), and only a small subset (7.4%) rating themselves at the highest familiarity level (rating 5/5).

This demographic profile highlights the characteristics of the convenience sample involved in alpha testing, which is not representative of the intended end-user population, namely older adults with cardiovascular risk.

6.2 Questionnaire

The results of the questionnaire proposed to the users, presented in Table 5.2, were analysed from two points of view: the usability of the exergame that was extracted with the SUS items will be reported in Section 6.2.1, while the findings regarding PENS and Avatar Embodiment items are described in Section 6.2.2 and Section 6.2.3.

6.2.1 Usability Evaluation

System usability was assessed using the SUS items that were integrated into the proposed questionnaire, as reported in Table 5.2. The distribution of individual SUS scores is illustrated in Figure 6.1, which also shows the corresponding grade rankings [74]. The scores ranged between 60 and 100, with a mean score of 81.2 ($\sigma = 11.02$), which places the system in the *Good–Excellent* usability range.

The system also reports a median of 80 and an interquartile range (IQR) of 15.63, reflected in the boxplot visualization of Figure 6.1 by the limited spread and no extreme outliers.

Additionally, when interpreting the SUS score through alternative benchmarking systems, the exergame achieved a Grade *A* classification [76, 77]. In parallel, the acceptability scale also positioned the exergame within the *"acceptable"* range, surpassing the minimum thresholds usually associated with marginal usability [78].

Item-level results are shown in Figure 6.2. The majority of participants agreed or strongly agreed that the system was well integrated (Q5: 36% agree, 39% strongly agree) and that most people would learn to use the exergame very quickly (Q7: 18% agree, 68% strongly agree).

Moreover, most participants disagreed with the statement that the exergame was unnecessarily complex (Q2: 39% disagree, 57% strongly disagree) and that they needed to learn a lot of things in order to use it (Q10: 21% disagree, 64% strongly disagree).

Conversely, the statement that received a more mixed response is the one affirming the intention to use the exergame frequently (Q1: 32% agree, 18% strongly agree).

6.2.2 Competence, Control and Presence Evaluation

The results from PENS items part of the proposed questionnaire are shown in Figure 6.3 with a Likert-7 chart featuring a color-coded distribution of responses based on agreement. The majority of the participants answered more positively to the two questions of the PENS regarding intuitiveness of controls, both to the direct statement *"The game controls are intuitive"* (Q12: 44% mostly agree, 30% strongly agree), and to the eventuality of remembering controls while playing (Q13: 33% mostly agree, 52% strongly agree). Moreover, the statement regarding feelings of competence also generated high levels of agreement (Q11: 48% mostly agree, 30% strongly agree).

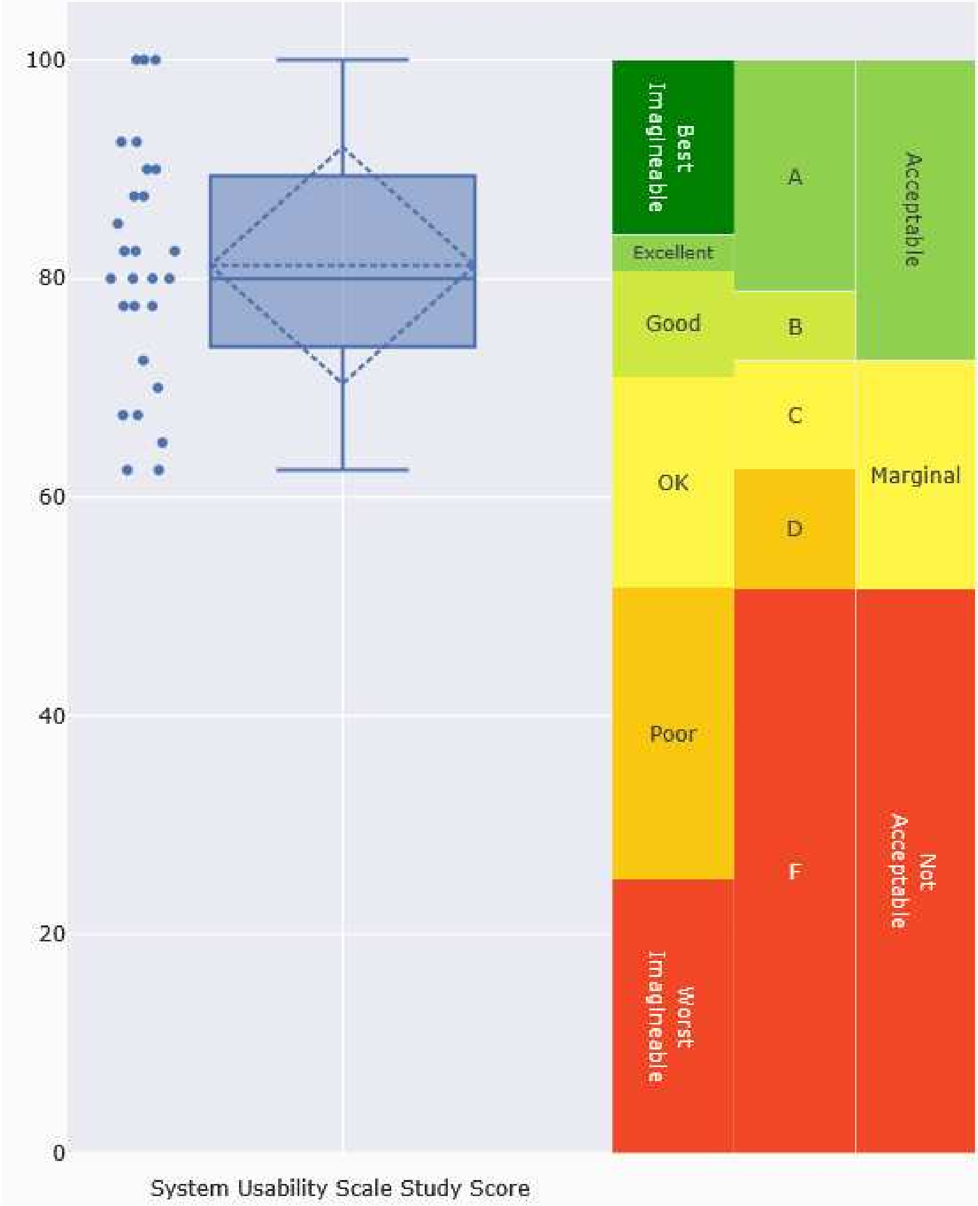


Figure 6.1: Boxplot chart of the distribution of SUS scores across participants. The colored ranges indicate adjective scale (from “Worst Imaginable” to “Best Imaginable”), grade (from "A" to "F") and acceptability (from "Acceptable" to "Not Acceptable"). Scores predominantly fall in the “Good” to “Excellent” range.

On the other hand, the sentences regarding presence report around one third of the participants in disagreement, especially when referring to the illusion of immersion in the virtual environment (Q14: 22% mostly disagree, 11% strongly disagree; Q15: 11% mostly disagree, 15% strongly disagree). The statement regarding the feeling of pride showed general agreement, even if one participant expressed total dissent (Q19: 30% somewhat agree, 33% mostly agree, 19% strongly agree).

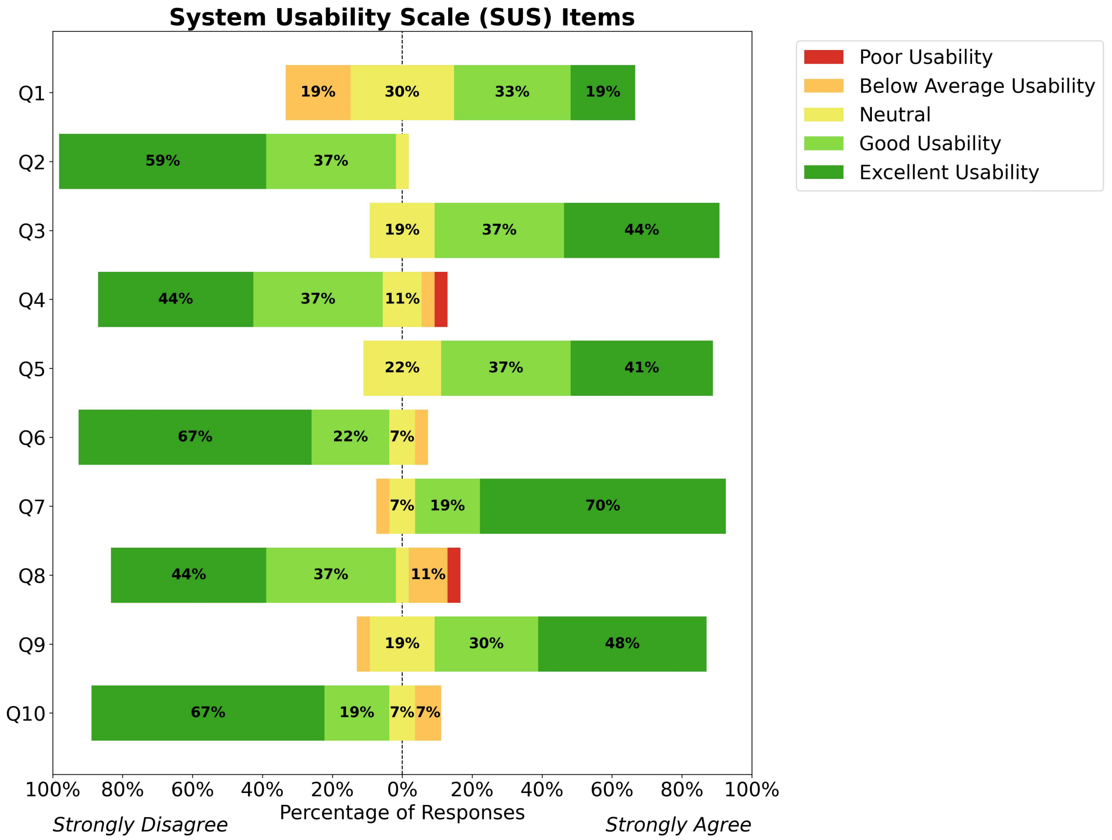


Figure 6.2: Item-wise distribution of responses to the SUS questionnaire. Percentages indicate the proportion of participants selecting each response option. The color coding reflects the value of each answer, with dark green representing the most favorable responses (i.e., "Strongly Agree" for odd-numbered items, "Strongly Disagree" for even-numbered items), followed by light green, yellow, orange, and red indicating progressively less favorable evaluations.

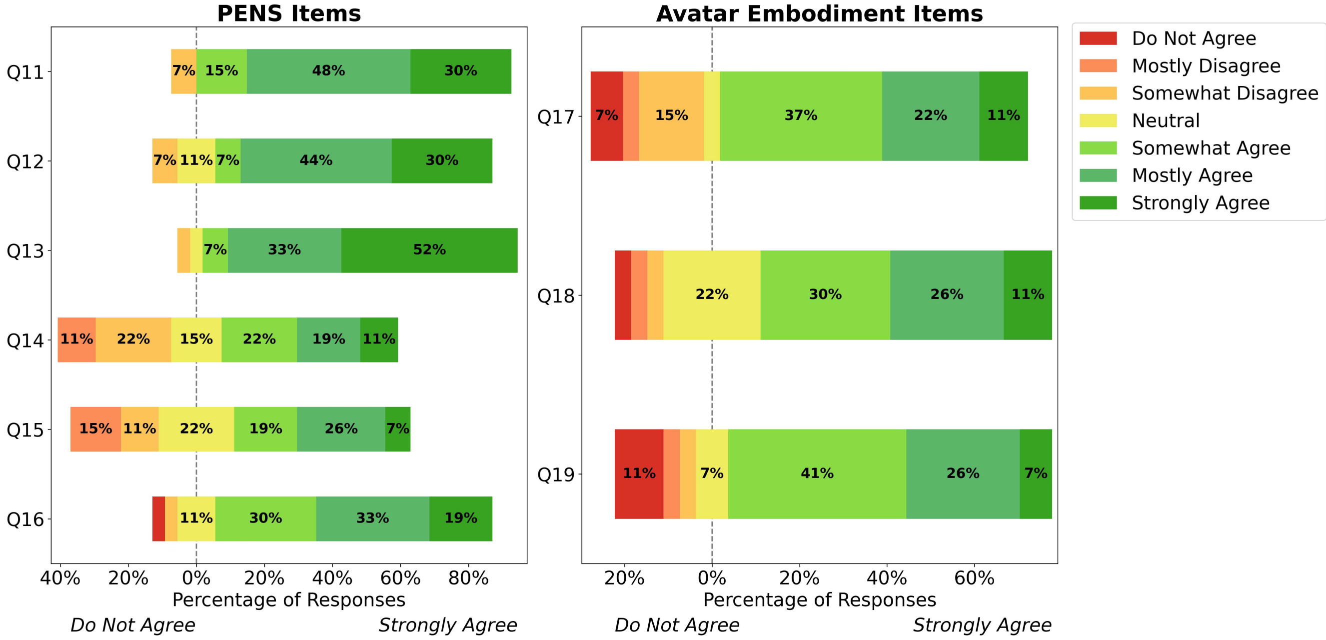


Figure 6.3: Item-wise distribution of responses for questionnaire items.PENS items (Q12–Q16), assessing perceived competence, autonomy, and related aspects of game experience. Avatar Embodiment items (Q17–Q19), assessing players' sense of identification and embodiment with the avatar. Percentages indicate the proportion of responses for each Likert scale option, with colors ranging from red (Do Not Agree) to dark green (Strongly Agree).

6.2.3 Avatar Embodiment Evaluation

The responses to the three avatar embodiment Likert-7 items are reported on the right chart in Figure 6.3. More than 50% of the participants showed varied levels of agreement both to the sentences discussing the avatar resemblance to their own body and to the allocation of their body inside the virtual world (Q17: 37% somewhat agree, 22% mostly agree, 11% strongly agree; Q18: 30% somewhat agree, 26% mostly agree, 11% strongly agree; Q19: 41% somewhat agree, 26% mostly agree, 7% strongly agree). Nonetheless, a non-negligible percentage of testers expressed either disagreement or neutrality towards these statements (Q17: 15% somewhat disagree, 4% mostly disagree, 7% strongly disagree; Q18: 22% neutral, 4% somewhat disagree, 4% mostly disagree, 4% strongly disagree; Q19: 7% neutral, 4% somewhat disagree, 4% mostly disagree, 11% strongly disagree).

6.3 Qualitative Feedback (Interviews)

In addition to the questionnaire data, participants were asked a few short interview questions aimed at exploring specific aspects of their experience with the exergame.

Regarding the immersive features of the game, a large majority (70%) identified the real-time movements of the avatar as the aspect that made them feel most present in the game, enabled by the pose tracking system in combination with T4A. Some participants emphasized this aspect directly, noting for instance: *"I get a direct response to my movements seeing the avatar replicate them in the game"*.

When asked about the less positive aspects of the experience, 37% mentioned the stepping motion as awkward, either in terms of comfort while performing it themselves or in observing it mirrored in the avatar, saying *"It's not very smooth"*, while 30% reported difficulties in clearly seeing the game objects due to their small size on the tablet screen.

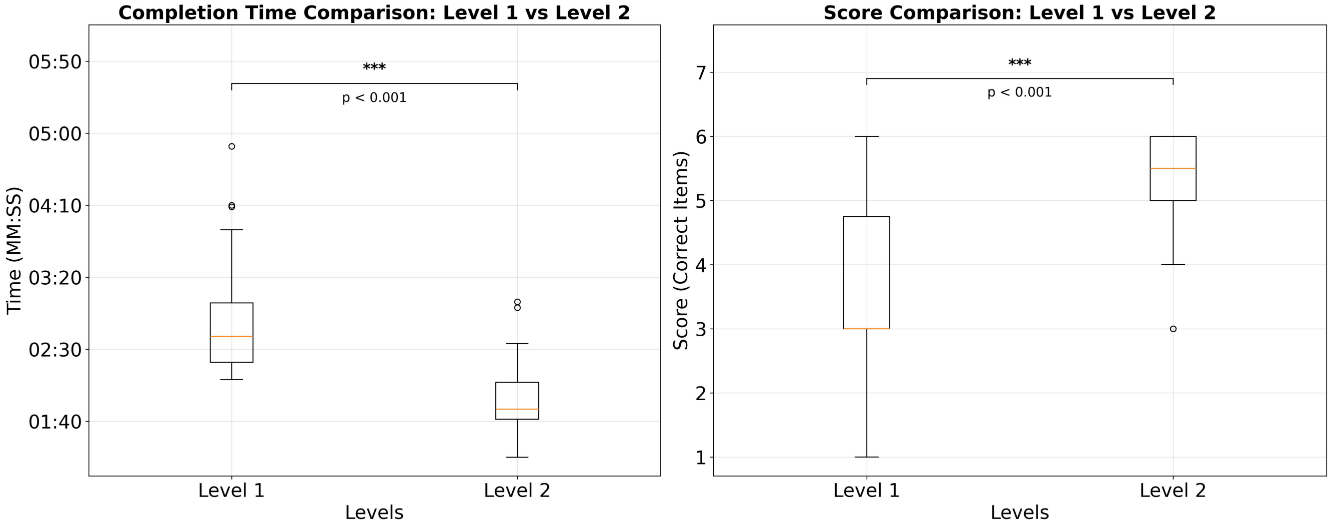
Concerning elements of confusion, the responses highlighted challenges primarily related to the tutorial and the guidance provided by the digital coach: 33% found it unclear that they were expected to remember items, 15% did not realize they would later have to make a choice, and thus that it was possible to do something incorrectly, affecting a score. Finally, 11% considered the tutorial in general to lack clarity, also considering the coach's explanation of the game controls, while 15% of the users declared that the task and controls were understood easily.

6.4 Completion Time and Score

A statistical comparison was conducted to examine differences in both completion time and performance scores between Level 1 and Level 2. The normality assumption was tested with the Shapiro-Wilk test, but since it was not met for either variable, Wilcoxon signed-rank tests were employed to compare the distributions.

As shown in Figure 6.4a, completion time was significantly reduced from $\mu = 2{:}51$ (min:s), $\sigma = 0{:}42$ in Level 1 to $\mu = 1{:}56$ (min:s), $\sigma = 0{:}26$ in Level 2, with test results $W = 0.00$, $p < .001$. The mean difference of 55 seconds ($\sigma = 0{:}38$) indicates a substantial reduction in task duration.

Similarly, the boxplot for correct item scores (Figure 6.4b) shows a statistically significant increase from Level 1 ($\mu = 3.62$, $\sigma = 1.27$) to Level 2 ($\mu = 5.19$, $\sigma = 0.98$), $W = 15.00$, $p < .001$, with a mean improvement of 1.58 points ($\sigma = 1.70$).



(a) **(b)**

Figure 6.4: Comparison of results between Levels 1 and 2. (a) Boxplot of completion time. (b) Boxplot of correct item scores.

Chapter 7

Discussion

7.1 Implementation Outcomes

The development of the system involved addressing a number of technical challenges, mainly associated with the integration of pose estimation and gesture recognition into the dual-task training framework.

7.1.1 DT-Tracking

QuickPose (QP) provided an existing model for pose estimation and gesture recognition, which could be adapted to the needs of the exergame. The choice of QP offered a complete framework, supporting not only pose estimation but also the identification of a variety of fitness movements. This opened opportunities for diverse dual-task exercise designs and enabled feedback on both movement execution and user positioning in front of the camera.

Nonetheless, QP's mobile implementation exhibited limitations in terms of accuracy when driving a 3D model, requiring the z-correction implementation described in Figure 4.1.1. The solution proved to be effective and allows for correct usage of the T4A framework for avatar animation. However, avatar animation algorithm is exposed to problems of stability, due to the direct use of the landmark coordinates: along with the tilt effect that has been corrected, the inaccuracies in z estimation also produce a gradually more accentuated stretching of the limbs that can occasionally cause jittering and deformations in the 3D model. Normalising limb proportions could represent one possible solution to mitigate these effects [67].

Moreover, the quality and realism of avatar movement provided by T4A's algorithm is strongly dependent on the pose estimation model: issues regarding the smoothness of the walking motion, also reported by the users, have their root in the accuracy of Mediapipe's model in computing the body keypoints for faster movements [67]. The problem must be systematically explored to search for an appropriate solution. This highlights the need for further refinement of the motion estimation and animation pipeline, although the proposed implementation already demonstrated functional feasibility.

7.1.2 DT-Game

The design effort prioritised the creation of a portable, simple and "plug-and-play" application. This goal is reflected in the resulting implementation: the straightforward menu (Figure 4.3) lists all the possible features, directly accessible with one or two touches. Concerns expressed by older participants in the focus group (Section 2.2) regarding excessive complexity and risk of abandonment were addressed by ensuring user independence, supported by the inclusion of task explanations delivered by the digital coach. While the double-application setup (DT-Tracking and DT-Game) remains a potential source of complexity, no calibration effort is required from the user, which facilitates accessibility.

The dual-task training was framed in the context of IADLs, but the decision to situate gameplay in a fantasy environment rather than a realistic one gave the exergame a distinctly gamified direction. This design choice sought to emphasise immersion and enjoyment as key determinants of sustained engagement. The setting also leaves open the possibility of future expansion, with additional tasks, narrative elements, or social interactions as features that could enhance motivation and user adherence.

The implementation of the digital coach relied on an on-device Text-To-Speech (TTS) tool. This lightweight integration supported multiple languages and ensured compatibility across devices, but the synthesised voice quality was suboptimal compared to generative AI solutions. While higher-quality voices could be integrated in the future, their computational cost may compromise system performance and add latency, particularly on mobile devices. At present, the current solution offers the most practical balance of efficiency and compatibility. Nonetheless, evaluating lightweight, more naturalistic voice solutions with older adults will be essential to determine whether they provide added value over the standard approach.

Moreover, the current TTS plugin allows for speech-to-text functionality to be enabled in future iterations, leaving open the option of user engagement with the coach at certain instances of the exergame task by using their voice (e.g., requesting or skipping tutorial explanations).

7.2 Testing

The demographics of the testing population have a role in interpreting the results: most participants were young adults with limited gaming and motion-based game experience, yet their evaluations were still positive. One older participant (in the 50+ age group) was especially enthusiastic, demonstrating attention and engagement, which suggests potential for the intended end-user group. However, given the mismatch between the testing sample and the target population of older adults with cardiovascular risk, these results can only be considered preliminary.

7.2.1 Usability Evaluation

The usability testing provided valuable insights into how the prototype was perceived, despite the convenience sample being predominantly composed of younger participants.

Overall, usability was rated very positively, as detailed in subsection 6.2.1. The system achieved a mean SUS score of 81, which is substantially higher than the benchmark 50th percentile score of 68 commonly reported in the literature [74, 76]. This score positions the prototype within the *Good–Excellent* usability range, confirming its acceptability and suggesting that the interaction design is robust. Importantly, the setup required only minimal guidance during the initial phases of the session, after which participants were able to engage with the system independently. These findings indicate strong potential for future evaluations with older populations, where ease of use and minimal onboarding are particularly critical.

The analysis of item-level responses in the SUS questionnaire, presented in Figure 6.2, shows a majority of positive evaluations of the system's usability in almost every question. Although the SUS alternates between positively and negatively worded statements, participants' answers systematically align in the direction indicating good usability—agreement for positive items and disagreement for negative ones. It can be noted that this response pattern highlights the coherence and perceived ease of use of the system across multiple aspects of interaction.

The only item showing a less pronounced positive tendency was the first one (*"I think that I would like to use this system frequently"*), which received more neutral or disagreeing responses. This can be attributed to the demographic of the testing sample, predominantly young adults, that doesn't match the target population of older adults, for which the exergame's features were designed.

7.2.2 User Experience Evaluation

The analysis of the user experience items (Q-11 to Q-19 of Table 5.2), whose results were shown in Figure 6.3, highlights two key aspects of the exergame's design. First, participants reported strong agreement with statements concerning their perceived competence in the task and the intuitiveness of the controls. This suggests that the mapping of fitness movements to in-game actions, the performing of specific exercises to collect objects based on their position, was well-received and supported a smooth interaction experience. These findings indicate that the choice of natural, body-based controls was effective in fostering usability and reducing barriers to gameplay.

In contrast, responses related to immersion and avatar embodiment were more mixed. While a majority expressed positive feelings, approximately one third of the participants disagreed on the identification with their avatar, thus reporting difficulty in experiencing a sense of body ownership and spatial presence in the game. This points to a potential area for improvement, as embodiment and immersion are central to sustaining engagement and enhancing the motivational potential of exergames [30].

This limitation was echoed in the post-questionnaire interviews, where several users described the stepping motion as awkward, either because it felt unnatural to perform or because the avatar representation did not move smoothly. Others mentioned difficulties in seeing objects clearly due to their size on the tablet screen, as well as confusion about the memory component of the tasks and the role of choice in gameplay.

Interviews further revealed that participants considered movement-related aspects to be the most valuable source of immersion, enjoying the direct visual feedback on their movements.

Finally, nearly half of the participants pointed to the tutorial or the explanation of the task as a source of confusion. Several participants reported that they had not paid sufficient attention during the tutorial or found it unclear that they were expected to remember the objects presented at the beginning of the level. As a result, when reaching the choice phase, some testers attempted to collect both items instead of selecting just one, without realizing that an incorrect choice would negatively affect their score. This confusion could be partly attributed to the digital coach's phrasing during the tutorial, which does not explicitly instruct users to remember the objects but rather encourages the users to collect a list of six specific items.

Interestingly, the user in the 50+ age group did not report such issues regarding the tutorial, understanding the task and remembering most objects from the first attempt. For the rest of the qualitative evaluations, he expressed thoughts aligning with the main findings, identifying the avatar animation as the most immersive feature and voicing his issue with the small size of the screen.

Despite these qualitative concerns, the quantitative results demonstrate that participants were able to improve significantly with repeated use. Completion time decreased and performance scores increased from Level 1 to Level 2, as shown in Figure 6.4. This suggests that even when initial instructions were perceived as unclear, users were nevertheless capable of exploring the game independently and achieving measurable gains in efficiency and accuracy after the second attempt.

These findings suggests that future refinements should focus on strengthening avatar embodiment, clarifying task instructions, and improving the fluidity of core movements to further enhance the exergame experience.

7.3 Limitations

While the results just discussed demonstrate the feasibility and potential of the prototype, several constraints related to the testing sample, technical implementation, and system architecture intervened in the development of this project and are summarised as the following:

- **Testing constraints:** The evaluations were carried out with a convenience sample of young adults. Consequently, the findings only provide hints about usability, presence, and immersion. Older adults, the intended end users, may respond differently, and their feedback could substantially reshape design priorities.

- **Technical constraints:** The system relied on QuickPose, which is a closed implementation with limited flexibility. While suitable for this prototype, its accuracy and stability remain to be improved for refined avatar animation.

- **Hardware constraints:** Testing was carried out on a small tablet screen, which limited usability. A setup featuring a bigger screen would be more suitable for independent and comfortable use by older adults.

- **System architecture:** The current implementation requires two separate applications (DT-Tracking and DT-Game). While functional, this setup complicates the plug-and-play nature of the system and reduces usability. Integration into a single application would improve accessibility.

7.4 Future Work

Acknowledging the limitations of this work also provides a clear roadmap for refinement. Building on the lessons learned from both technical implementation and user testing, several directions for future development can be identified:

- **Improving usability:** Efforts should be made to overcome the limitations of the small tablet screen and the dual-app setup. A larger or more flexible display solution, combined with a single integrated application, would enhance comfort and independence of use.

- **Technical improvements:** Future iterations should refine the motion estimation and avatar animation pipeline. Enhancing physical constrains for the 3D avatar model could improve realism and embodiment, addressing the current limitations.
- **Content expansion:** In this project, only one type of level was implemented. The modularity of the design, however, allows for easy expansion with additional combinations of tasks and mechanics. This offers the opportunity to create a wider variety of training levels, where users can choose their preferred exercises, and a progression system, (e.g., experience points) could sustain motivation across sessions while ensuring sufficient gameplay for meaningful training [29].
- **Testing with the target population:** Following the improvements to the exergame system, evaluation and testing must then involve older adults at risk of MCI. Their feedback will provide a realistic assessment of usability, motivation, and training potential.

In sum, this work succeeded in delivering a functional prototype that demonstrated feasibility and potential. At the same time, the identified limitations and future work directions highlight the path toward creating a robust, user-centered exergame capable of addressing the needs of aging populations at risk of cognitive and physical decline.

Chapter 8

Conclusions

The goals of this thesis were to design, develop, and preliminarily evaluate an exergame system aimed at addressing the physical, cognitive, and motivational challenges associated with aging, specifically regarding the prevention of Mild Cognitive Impairment. This project integrated multiple perspectives and domains, including human-computer interaction, dual-task training, pose estimation, and feedback techniques, resulting in a functional prototype for mobile devices that merges physical activity with cognitive engagement in a user-centered platform.

One main achievement of this work lies in the successful integration of multiple design features, including motion tracking, avatar-driven interaction, and an embedded coaching system. The avatar-based virtual coach was designed to deliver real-time, personalized feedback and encouragement, aiming to sustain user engagement and thus long-term adherence in preventive interventions. In addition to this, progress tracking and performance feedback mechanisms were introduced to ground users' training experience in measurable outcomes.

The testing phase confirmed the system's usability, with results indicating positive perceptions of competence, intuitiveness, and overall user experience. Although the participants' sample was limited and not representative of the intended target group, the results provide preliminary evidence of feasibility and potential. Importantly, qualitative feedback highlighted the real-time avatar animation as the most immersive feature of the exergame, supporting the feeling of presence and strengthening engagement together with the virtual coach. These findings point toward immersive, presence-enhancing features as a particularly promising direction for future research and refinement.

Ultimately, this thesis contributes with a technical prototype and a design framework for future exergame interventions targeting cognitive health promotion in aging populations. The proposed solution demonstrates that engaging, low-cost, and accessible tools can be developed on mobile platforms.

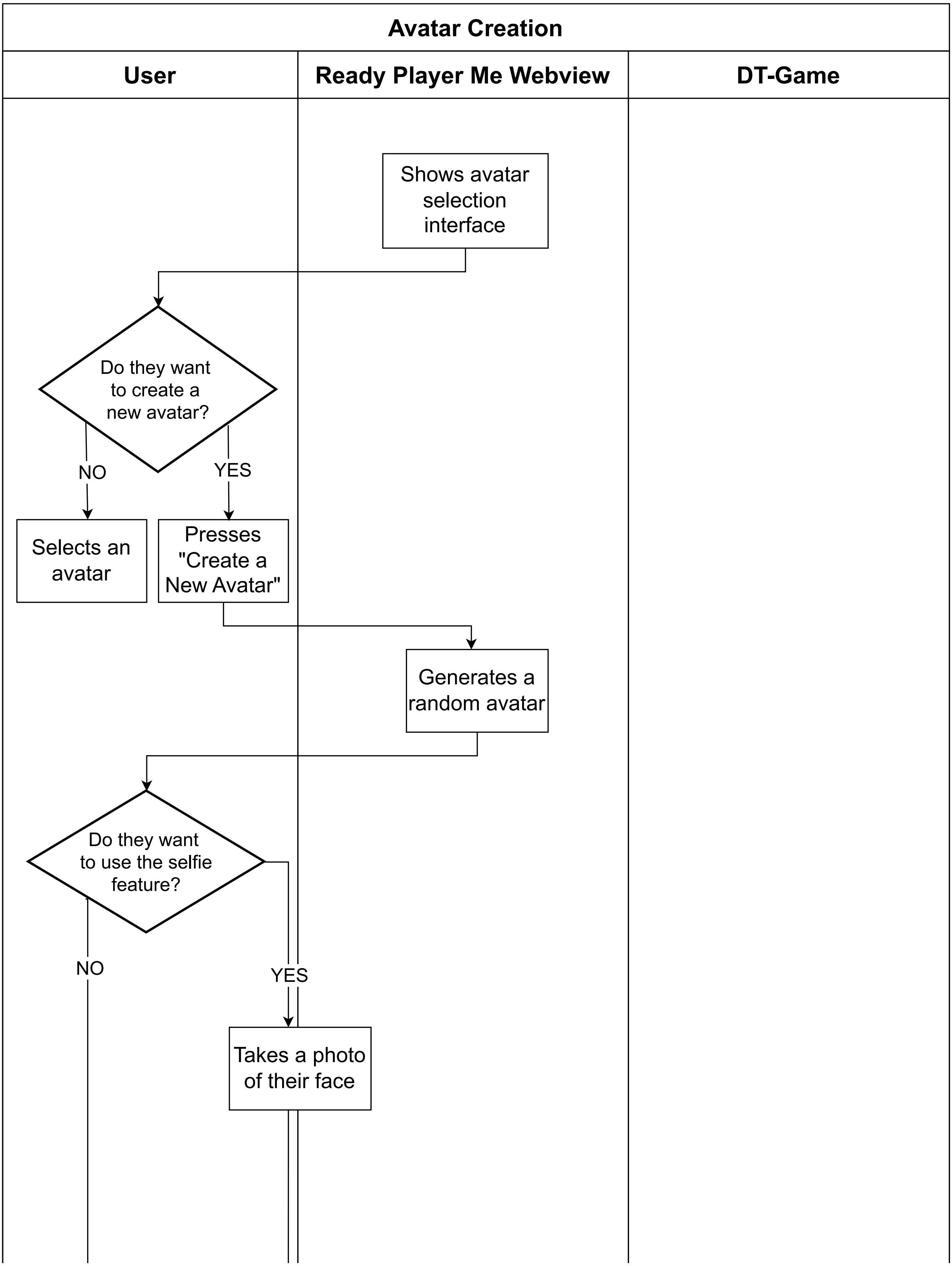
This work thus highlights the technical feasibility and usability of a dual-task exergame designed for cognitive stimulation and physical engagement. While preliminary, the findings suggest that immersive features and user-centered design are key to maximizing the potential of exergames as preventive interventions.

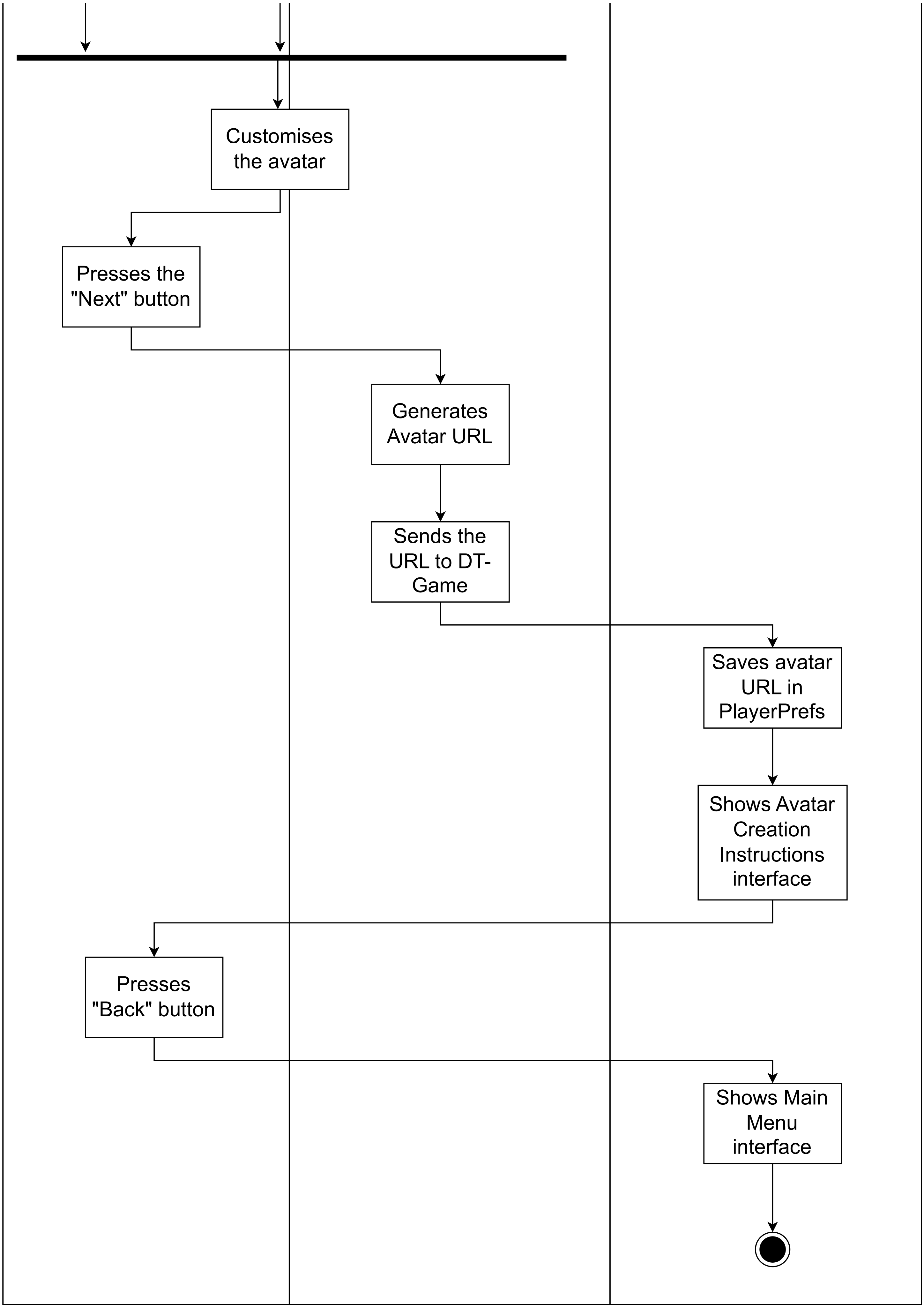
Appendices

The appendices contain the following supplementary material:

- Appendix A – Avatar Creation Swimlane Chart
- Appendix B – Exergame Level Swimlane Chart
- Appendix C – Consent Form
- Appendix D – Exergame Context
- Appendix E – Background Information and Questionnaire proposed to Users
- Appendix F – Complete PENS Questionnaire
- Appendix G – Complete Avatar Embodiment Questionnaire

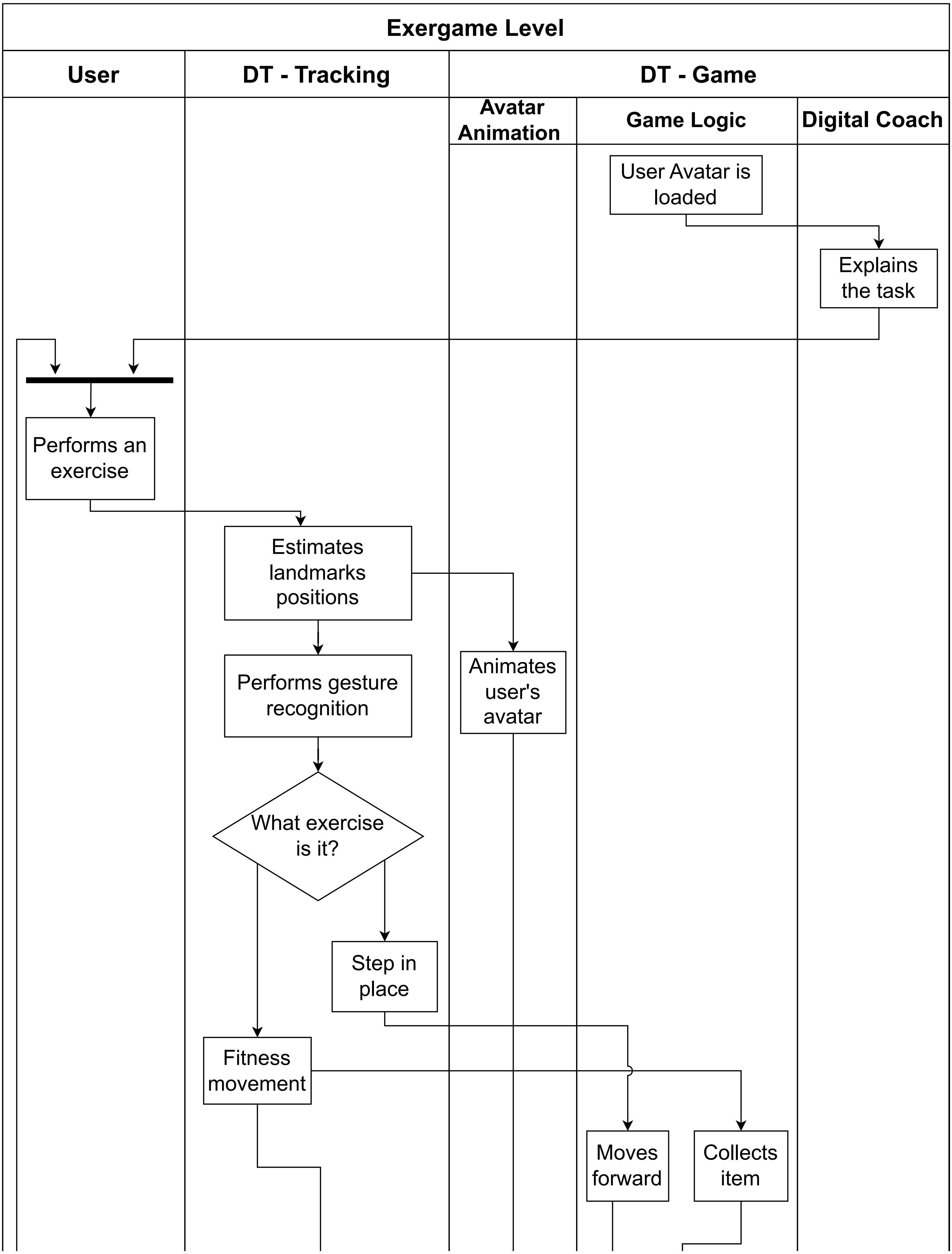
Appendix A - Avatar Creation Swimlane Chart

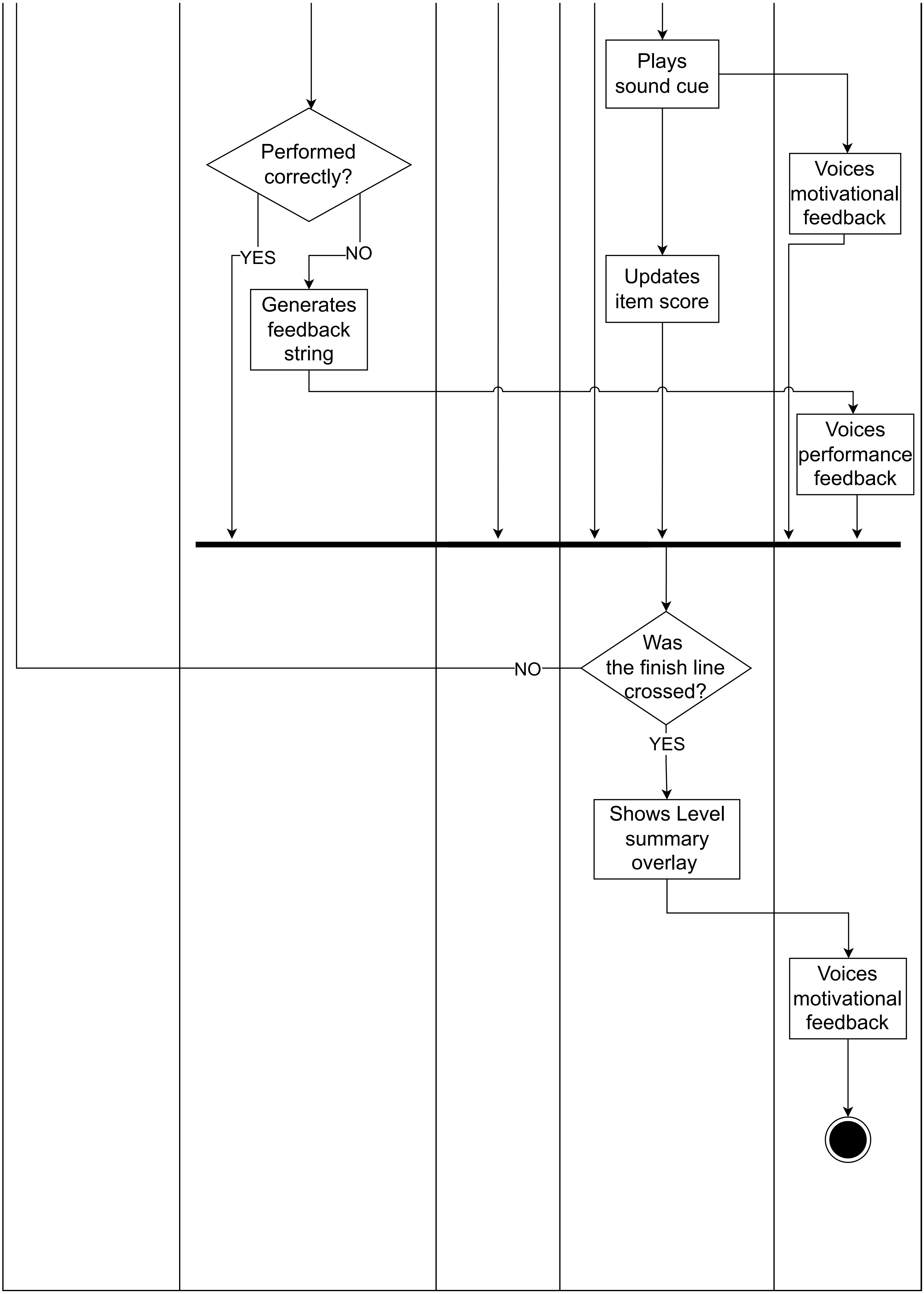




Customises the avatar
Presses the "Next" button
Generates Avatar URL
Sends the URL to DT-Game
Saves avatar URL in PlayerPrefs
Shows Avatar Creation Instructions interface
Presses "Back" button
Shows Main Menu interface

Appendix B - Exergame Level Swimlane Chart




Plays sound cue
Performed correctly?
Voices motivational feedback
YES
NO
Generates feedback string
Updates item score
Voices performance feedback
Was the finish line crossed?
NO
YES
Shows Level summary overlay
Voices motivational feedback

Appendix C – Consent Form

Consent Form for Master Thesis Research

We are conducting research as a part of a Master Thesis on Dual-Task Exergames featuring Virtual Coaches. The goal of this study is to test an exergame prototype and its features. In this context, you will create a virtual avatar using a picture of your face and interact with the game by completing simple physical exercises. You will then answer a questionnaire on your experience and we will ask you to provide demographics information (e.g., age, gender), along with other information regarding your background. The experiment is expected to last between 20 and 30 minutes.

I, the undersigned:
Surname, first name ……………………………………………………………………………………........

- Agree to participate in this research on the use of Dual-Task Exergames conducted by the HumanTech Institute (HEIA-FR) in collaboration with Politecnico di Torino. This research is conducted under the supervision of Elena Mugellini.
- Declare to have been informed, orally and in writing, by one of the investigators of the aims of the research as well as the tasks to be carried out.
- Affirm that I have received satisfactory answers to the questions I asked in relation to my participation in this study.
- Take part in this study voluntarily. I can, at any time and without having to provide any justification, revoke my consent to participate in this study.
- Declare that I had enough time to make my decision.
- Affirm to be aware that my responses and participation will remain strictly confidential: individual data will be collected by project collaborators and processed anonymously (the names will be replaced by codes). The results will only be presented in a way that ensures no possibility of identifying individual participants.
- Have been informed that all data processed as part of the research project will be collected and stored securely and anonymously, in accordance with the Federal Data Protection Act (RS 235.1). All data is collected and published strictly in anonymous form.
- Authorize the researchers to use, analyze, and disseminate, without time limitation, the data collected during the experiment (including notes and questionnaire responses).
- ☐ I additionally consent to the use of photos/videos taken for valorisation purposes, with the guarantee that I will not be recognizable and may request their removal.
- Accept that anonymized data may be shared with other research groups or institutions strictly for research purposes.

Place, Date: ……………………………………… Signature: …………………………………………………

Appendix D – Exergame Context

User Test for Dual-Task Exergame

Context

Welcome! You will be doing a preliminary test of an exergame that combines physical exercises with cognitive challenges, like memory and attention tasks. The game is designed for daily use to help adults over 60 maintain both mental and physical health and reduce the risk of mild cognitive impairment (MCI). You will interact with the game using your movements, tracked in real time through the tablet's webcam.

In the game, you live in a small village set in a fantasy world. Your coach is a trusted friend who accompanies you on tasks and adventures around the village, offering guidance and suggestions along the way. During the test, you will meet her to complete one of these tasks together.

Getting Started:

1. Open the app **DT-Game** and create your avatar by selecting **"Create Avatar"** from the menu and following the instructions. When you're back to the menu, minimize the game.
2. Open the **DT-Tracking** application, which enables motion tracking.
3. Find a comfortable position in the room where the camera can clearly see your whole body from head to toe.
4. Minimize the DT-Tracking application (leave it running in the background).
5. Return to the game to play Level 1.

Appendix E – Background Information and Questionnaire proposed to Users

Background Information

#	Item	Response
	Demographics	
1	Age	18–25 26–35 36–45 46–59 60+ Prefer not to say
2	Gender	Female Male Non-binary Other Prefer not to say
3	What is the highest level of education you achieved?	No formal education Compulsory High School Bachelor's Master's Doctorate Other
4	What is your field of work/study?	Open response
	Gaming habits	**Response**
5	How often do you play video games?	1 2 3 4 5
6	How familiar are you with motion-based games?	1 2 3 4 5
7	How physically active are you in daily life?	1 2 3 4 5

Usability and User Experience Questionnaire

#	Item	Response						
	System Usability Scale (SUS) items	***Strongly disagree***						***Strongly agree***
1	I think that I would like to use the exergame frequently.	1	2	3	4	5		
2	I found the exergame unnecessarily complex.	1	2	3	4	5		
3	I thought the exergame was easy to use.	1	2	3	4	5		
4	I think that I would need the support of a technical person to be able to use the exergame.	1	2	3	4	5		
5	I found the various functions in the exergame were well integrated.	1	2	3	4	5		
6	I thought there was too much inconsistency in the exergame.	1	2	3	4	5		
7	I would imagine that most people would learn to use the exergame very quickly.	1	2	3	4	5		
8	I found the exergame very awkward to use.	1	2	3	4	5		
9	I felt very confident using the exergame.	1	2	3	4	5		
10	I needed to learn a lot of things before I could get going with the exergame.	1	2	3	4	5		
	Player Experience of Need Satisfaction (PENS) items	***Do Not Agree***						***Strongly agree***
11	I feel competent at the game.	1	2	3	4	5	6	7
12	The game controls are intuitive.	1	2	3	4	5	6	7
13	When I wanted to do something in the game, it was easy to remember the corresponding control.	1	2	3	4	5	6	7
14	When playing the game, I feel transported to another time and place.	1	2	3	4	5	6	7
15	When moving through the game world I feel as if I am actually there.	1	2	3	4	5	6	7
16	When I accomplished something in the game I experienced genuine pride.	1	2	3	4	5	6	7
	Avatar Embodiment items	***Do Not Agree***						***Strongly agree***
17	It felt as if my (real) body were turning into an 'avatar'.	1	2	3	4	5	6	7
18	At some point it felt that the virtual body resembled my own (real) body, in terms of shape, skin tone or other visual features.	1	2	3	4	5	6	7
19	I felt as if my body was located where I saw the virtual body.	1	2	3	4	5	6	7

Appendix F - Complete PENS Questionnaire

PENS v1.6 – Subscale Scoring

<u>Administration Guidelines:</u>

- Respondents typically rate their level of agreement to each item using a 7-point Likert scale (1= Do Not Agree, 7=Strongly Agree);
- All items are weighted equally in scoring;
- Items are randomized in their order when presented to participants;
- Reverse-scored items are indicated by “(-)”;
- Questions are framed by the following stem:

“Reflect on your play experiences and rate your agreement with the following statements:”

<u>PENS: Competence</u>
Reflect on your play experiences and rate your agreement with the following statements:

1. I feel competent at the game.
2. I feel very capable and effective when playing.
3. My ability to play the game is well matched with the game's challenges.

<u>PENS: Autonomy</u>
Reflect on your play experiences and rate your agreement with the following statements:

1. The game provides me with interesting options and choices
2. The game lets you do interesting things
3. I experienced a lot of freedom in the game

<u>PENS: Relatedness</u>
Reflect on your play experiences and rate your agreement with the following statements:

1. I find the relationships I form in this game fulfilling.
2. I find the relationships I form in this game important.
3. I don’t feel close to other players. (-)

Presence/Immersion

1. When playing the game, I feel transported to another time and place.
2. Exploring the game world feels like taking an actual trip to a new place.
3. When moving through the game world I feel as if I am actually there.
4. I am not impacted emotionally by events in the game (-).
5. The game was emotionally engaging.
6. I experience feelings as deeply in the game as I have in real life.
7. When playing the game I feel as if I was part of the story.
8. When I accomplished something in the game I experienced genuine pride.
9. I had reactions to events and characters in the game as if they were real.

PENS: Intuitive Controls:

1. Learning the game controls was easy.
2. The game controls are intuitive.
3. When I wanted to do something in the game, it was easy to remember the corresponding control.

Appendix G - Complete Avatar Embodiment Questionnaire

Please select your level of agreement with the following statements:

"During the experiment there were moments in which…

Q1. I felt as if the virtual body I saw when I looked down was my body"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q2. It felt as if the virtual body I saw was someone else"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q3. It seemed as if I might have more than one body"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q4. I felt as if the virtual body I saw when looking in the mirror was my own body"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q5. I felt as if the virtual body I saw when looking at myself in the mirror was another person"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q6. It felt like I could control the virtual body as if it was my own body"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q7. The movements of the virtual body were caused by my movements"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q8. I felt as if the movements of the virtual body were influencing my own movements"

strongly disagree	disagree	somewhat disagree	neither agree nor disagree	somewhat agree	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q9. I felt as if the virtual body was moving by itself"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q10. It seemed as if I felt the touch of the ____ in the location where I saw the virtual body touched"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q11. It seemed as if the touch I felt was located somewhere between my physical body and the virtual body"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q12. It seemed as if the touch I felt was caused by the ____ touching the virtual body"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q13. It seemed as if my body was touching the ____"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q14. I felt as if my body was located where I saw the virtual body"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q15. I felt out of my body"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q16. I felt as if my (real) body were drifting towards the virtual body or as if the virtual body were drifting towards my (real) body"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q17. It felt as if my (real) body were turning into an 'avatar' body"

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q18. At some point it felt as if my real body was starting to take on the posture or shape of the virtual body that I saw”

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q19. At some point it felt that the virtual body resembled my own (real) body, in terms of shape, skin tone or other visual features”.

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q20. I felt like I was wearing different clothes from when I came to the laboratory”

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q21. “I felt that my own body could be affected by ____”

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q22. I felt a ____sensation in my body when I saw ____”

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q23. When ____ happened, I felt the instinct to ____”

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q24. I felt as if my body had ____”

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

Q25. I had the feeling that I might be harmed by the ____ “

strongly disagree	*disagree*	*somewhat disagree*	*neither agree nor disagree*	*somewhat agree*	agree	strongly agree
(-3)	*(-2)*	*(-1)*	*(0)*	(1)	(2)	(3)

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