Supporting Physical Training in Healthy Older Adults Through Biocybernetic Adaptation and Exergaming

DOCTORAL THESIS

John Edison Muñoz Cardona
DOCTORATE IN INFORMATICS ENGINEERING
SPECIALTY IN HUMAN COMPUTER INTERACTION

UNIVERSIDADE da MADEIRA
A Nossa Universidade
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October | 2018

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QREN QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL PORTUGAL 2007.2013

REGIÃO AUTÓNOMA DA MADEIRA

REPÚBLICA PORTUGUESA

UNIÃO EUROREIA
Fundo Social Europeu

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"…psychophysiological training technologies are poised to exploit the revolution in interactive multimedia home entertainment for the personal improvement, not just the diversion, of the user."

Alan Pope - 1996

Abstract

Physical inactivity in older adults is commonly associated with the development of chronic diseases, poor maintenance of functional status, possible cognitive declines and the loss of physical independence. With the aim of reducing the social and economic burdens generated by the high percentages of older adults in the population, active aging programs have been intensively promoted. These programs, however, suffer from low rates of adherence and a lack of exercise's personalization that end up in demotivated older adults. Exercise videogames (Exergames) have been established as a fun and enjoyable method to promote physical activity, by using competition, timely feedback, and fun, they counteract the monotony of exercise routines. Although frequently attractive, the use of Exergames for exercise promotion in older adults still faces challenges in demonstrating effectiveness regarding functional fitness, cognitive functions, and game user experience. Moreover, the long-term effects of using Exergames as a structured exercise program in the older population have been rarely investigated. To tackle these limitations in Exergaming research, this thesis uses two different Human-Computer Interaction (HCI) techniques: human-centered design and physiological computing. The main objective is to maximize Exergaming effectiveness via: i) providing a more personalized, diversified and enjoyable game experience through custom-made Exergames and ii) optimizing the body responses while exercising with a physiologically intelligent software layer. First, a set of four Exergames that covers aerobic endurance, muscular strength and motor ability fitness domains were carefully designed via contextual design. Secondly, the biocybernetic loop construct from physiological computing is used to improve the cardiovascular performance of older adults through an Exergame that adapts its difficulty based on game performance and exertion levels, thus persuading players to exert in the desired and recommended levels. Two cross-sectional and two longitudinal controlled studies were completed in local senior gymnasiums with active older adults addressing multiple research questions to unveil the role of customized and adaptive Exergames in promoting physical activity. We demonstrated how attractiveness and effectiveness can be successfully combined in Exergaming design to deliver encouraging and motivating exercises that are equivalent (or sometimes better) to conventional training methods. Moreover, we illustrated the design of a set of physiological computing software tools that can be extensively used for biocybernetic adaptation in videogames, and physiological signal post-processing and interpretation.

Keywords: Exergames, physiological computing, human-centered design, biocybernetic loop, contextual design, effectiveness.

Resumo

A inatividade física nos idosos está comumente associada ao desenvolvimento de doenças crónicas, fraca conservação do estado funcional, possíveis declínios cognitivos e a perda de independência. Com o objetivo de reduzir os fardos sociais e económicos gerados pelas altas percentagens de idosos na população, programas de envelhecimento ativo têm sido promovidos intensivamente. No entanto, estes programas sofrem de baixas taxas de aderência e uma falta de personalização do exercício que resulta em idosos desmotivados. Videojogos de exercício (Exergames) são reconhecidos como um método divertido e agradável de promoção da atividade física, através do uso da competição, feedback pertinente, e diversão estes contrariam a monotonia das rotinas de exercício convencional. Apesar de atraente, o uso de Exergames para a promoção de exercício nos idosos ainda se depara com obstáculos em demonstrar a sua eficácia em termos de melhorias de fitness funcional, funções cognitivas, e experiência do jogador. Ademais, o efeito a longo termo do uso de Exergames como programa estruturado de exercício para idosos raramente foi investigado. Para lidar com essas limitações na área de Exergames esta tese usa duas técnicas de Interação Humano-Computador (HCI) diferentes: design centrado no usuário e computação fisiológica. O principal objetivo é o de maximizar a eficácia da prática de Exergames através de: i) fornecimento de uma experiência de jogo mais personalizada, diversificada e agradável em Exergames feitos à medida e ii) otimização das respostas corporais durante o exercício em Exergames com uma camada de software fisiologicamente inteligente. Primeiro, um conjunto de quatro Exergames abrangentes dos domínios de resistência aeróbica, força muscular e capacidade motora foram cuidadosamente projetados por meio de design contextual. Em segundo lugar, o conceito de malha biocibernética fechada de computação fisiológica foi usada para melhorar o desempenho cardiovascular de idosos através de um Exergame que adapta a sua dificuldade com base no desempenho e níveis de esforço do jogador, persuadindo-os a exercerem os níveis desejados e recomendados. Dois estudos transversais e dois estudos longitudinais controlados foram concluídos em ginásios locais com idosos ativos, abordando várias questões de investigação para desvendar o papel de exergames customizados e adaptativos na promoção da atividade física. Demonstramos como a atratividade e a eficácia podem ser combinadas com sucesso no design de Exergames para fornecer exercícios encorajadores e motivadores que são equivalentes (ou por vezes melhores) aos métodos de treino convencionais. Além disso, apresentamos o design de um conjunto de ferramentas de software de computação fisiológica que podem ser amplamente utilizadas para adaptação biocibernética em videojogos e pós-processamento e interpretação de sinais fisiológicos.

Palavras-chave: Exergames, computação fisiológica, desenho centrado no utilizador, malha biocibernética, design contextual, eficácia.

Acknowledgements

This work was supported by ARDITI (*Agência Regional para o Desenvolvimento da Investigação Tecnologia e Inovação*) through the Project M1420 - 09-5369-FSE-000001 - PhD Scholarship, Portuguese Foundation for Science and Technology (FCT) through the Augmented Human Assistance project (CMUP-ERI/HCI/0046/2013) and LARSyS (*Labóratorio de Robótica e Sistemas em Engenharia e Ciência*) through the *Projeto Estratégico* UID/EEA/50009/2013. I would like to thank the Madeira Interactive Technologies Institute's (M-iti) community, the NeuroRehabLab researchers and the healthcare professionals at the senior gymnasiums Santo Antonio and São Martinho in Funchal, Madeira. Special thanks to all senior users that were always committed to participate and contribute on each study here documented.

Contents

1 Motivation & State of the art

This chapter gives a brief explanation of the motivations and trends that drove this research. It also provides a synthesized description of the theoretical frameworks and the state-of-the-art investigated to study Exergames for exercise prescription in older adults. A concise review of significant contributions in the fields of human-centered design and physiological computing applied in Exergaming scenarios is described, and the remaining challenges are highlighted.

1.1 Motivation

Physical inactivity is now recognized as a global public health priority and is the fourth leading cause of death worldwide [1]. More than 30% of the world population is not meeting the minimum recommendations for physical activity, and 6-10% of all deaths from non-communicable diseases may be attributed to sedentarism [2]. There has been a rapid change in the demographic profile in the last decades. According to the World Health Organization (WHO), the number of people around 60 years and over will double between 2000 and 2050 [1]. In fact, the projected population aged 60+ in 2035 is 30.4% in Europe and 25.8% in the USA. Just in Portugal, the country's rate of aging is 129 (129 older adults against 100 young people) [3]. In addition, high levels of inactivity have caused adverse effects on the way people are aging, impacting their social and economic well-being. Data from the Global Age Watch Index in 2015 render Portugal as the third worst country in Europe for older adults' well-being [4].

One of the models for prolonging the average human life expectancy is called "active aging", which was developed by the WHO. Active aging explores the interactions of older adults in an age-integrated society, going beyond the concept of being physically active [5]. In this approach, older adults are seen as active participants in economic, social and cultural affairs. To support physical activity, Information and Communication Technologies (ICT), which are now ubiquitous, show potential for increasing exercise and behavioral change through global positioning systems, wearable devices, persuasive technologies and interactive videogames [6]. Specifically, body motion has been introduced as an input modality to commercial videogames, the so-called Exergames. Exergames aim at promoting physical activity embellishing the experience via gamification elements that engage players through interactivity, game challenges, points, rewards, and entertainment, therefore enabling longer-term adoption and better adherence to training programs than conventional methods [7]. Exergames have been under investigation for the last years showing a high potential to promote physical activity in multiple environments and populations [6].

Research with exergames has shown encouraging findings in motivation for exercising [8], improvements in cognitive function [9] and physiological energy expenditure [10]. Still, several reviews in the field point out the need for additional research in the long-term adherence of Exergames specifically designed for the older population [11]–[13]. One of the crucial

aspects to ensure Exergames' effectiveness in producing health benefits is a proper design process. Commercial Exergames are frequently used by researchers to explore multiple effects of Exergaming programs [14] [15], but this repurposing approach raises concerns. Older adults care applications have specific requirements for user interfaces, exercises, and game design that are not considered in commercial Exergames, thus limiting the impact of interventions [16]. Also, since the older adult population is very heterogeneous regarding needs, deficits and co-morbidities, Exergames need to be specifically tailored to each to maximize the impact in their health [11], [17], [18]. For instance, game contents specifically designed for older adults (which are typically non-game experts) must provide adapted gameplay to facilitate a sustained motivation and to stimulate a frequent use of the tool.
Further, intervention's success should not be directly linked to game scoring. Objective evaluation methods need to be carefully planned with healthcare experts and integrated into Exergames to provide as much feedback on progress as possible [16]. Moreover, the literature is scarce in long-term investigations and the assessment of the impact of adaptive Exergames in senior population is missing [19]. Summarizing, Exergames for senior adults need to balance sustainable motivation [20], a monitoring and quantification of user's performance [21], and adaptation to provide Exergame personalization adjusted to user's needs [22]. There are two frameworks from the Human-Computer Interaction (HCI) field that have the potential to respond adequately to the abovementioned Exergaming challenges: i) human-centered design methods and ii) physiological computing technologies.

From one side, the human-centered design might help in the complex task of model older adults, which are commonly reduced regarding game preferences, exercise motivators and technology literacy [23]. In Exergaming research, it is common to associate the aging process merely with weakness and debilitation. This reductionist view of older adults limits the design of completely fun and highly personalized Exergames that can be adopted in exercise promotion scenarios such as senior care centers or gymnasiums [24]. Despite its extensive use in many software engineering processes and applications [25], human-centered methodologies still constitute a complex and poorly understood the method to design compelling and effective Exergames for the older population [26]. Inquiring in physiological responses and novel computing approaches in intelligent systems are also part of the ambitious and multidisciplinary agenda of Exergaming research [27]. Novel adaptation paradigms based on biocybernetic technologies that use real-time physiological data to inform systems about human performance may have a meaningful impact on Exergames design [28], [29]. However, a significant limitation with physiological adaptation and its application on Exergames is the inherent complexity of studying physiological phenomena while exercising as well as the challenges in system implementation and further replication [30], [31].

Finally, past work in both human-centered and physiological computing approaches applied in Exergaming fails in providing substantial evidence on the impact of personalized Exergames beyond short-term research trials.

Therefore, this research aims at extending current Exergaming approaches for exercise promotion in older adults by exploring human-centered design and physiological adaptation techniques. The ultimate goal is to increase the effectiveness of exercising with novel, highly personalized and dynamically adaptive Exergames. Therefore, providing solid scientific evidence of long-term technology adoption as well a set of freely available software tools to aid the integration of physiological adaptation in Exergames.

1.2 Research Background and State of the Art

1.2.1 Fitness Assessment in Older Adults

The American College of Sports and Medicine (ACSM) and the American Heart Association (AHA) established a set of recommendations for physical activity which describes the amounts and types of physical activity to promote health, prevent diseases and functional limitations in older adults [32]. The training areas are described as follows:

- Aerobic fitness: maintaining adequate levels of aerobic endurance - circulatory and respiratory systems working together to supply oxygen to the body during sustained physical activity - has been associated with: a) increases in a person's functional mobility and b) decreases in the risk for medical conditions such as cardiovascular disease, diabetes, obesity and high blood pressure [33]. The guidelines establish older adults to exert at least 150 minutes per week (accumulated) at moderate intensity (5-6 in a 0-10 scale) with exercises varying from walking, swimming or stepping.
- Musculoskeletal (also called muscle-strengthening) fitness: associated with muscular strength, it has been shown that sufficient strength of arms and legs is imperative to avoid a decline in function in daily life activities, especially in older populations [34]. Exerting the major muscles groups (e.g., legs, arms, shoulders) with a range of 10-15 repetitions with adequate weights for at least two times per week are the recommended levels by ACSM.
- Flexibility (or limberness): defined as the ability to move joints and muscles covering their full range of movement. Regular and proper stretching exercises will soften the declining effect of flexibility during the aging process [35]. For good results, older adults should stretch at least two days per week for a minimum of 10 minutes accomplishing mild tightness in the muscle following the ACSM guidelines.
- Balance: to minimize risks of injury associated with falls, older adults should perform exercises to strengthen the ability to move or to remain in a stable position without losing control [32]. Exercises should be performed two to three days per week lasting 10 to 30 seconds and ideally combined with leg strength training.

The guidelines apply to all adults aged 65+ years as well as to adults aged 50-64. Several reviews in the domain of Exergames for older adults highlighted the importance of addressing multiple physical functions in a structured way following health standards and well-defined protocols [15]

[11]. In the older population, accomplishing the ACSM guidelines of physical activity represents a reduction of risks associated with diabetes, coronary heart disease, hypertension, osteoporosis, and obesity and weight control [36]. Moreover, several aspects of mental health can also be positively impacted via regular physical activity at the adequate intensity levels [37]. Particularly in the older population, exercise intensity should be one that activates the body muscles and stresses the heart without producing risks associated with over-exercise (e.g., falls, excessive fatigue) [32]. Indeed, one of the significant findings of the 2018 physical activity guidelines advisory committee scientific report [1] was that exercising at moderate to vigorous physical activity (MVPA) improves the quality of sleep reduces anxiety symptoms, improves cognition and reduces blood pressure among others. MVPA is a measurement of the level of exercise intensity that is computed through Metabolic Equivalents (METs). A MET is a ratio that compares a person's working metabolic rate to their resting metabolic rate. It is well known that a person sitting quietly would be considered one MET [6]. Thus, moderate-intensity physical activity is defined as 3 – 6 METs, while vigorous-intensity physical activity is defined as activities above 6 METs. This means that the MET's threshold to define MVPA is any activity over 3 METs [6]. Another essential and more straightforward way to measure the intensity of physical activity is through ratings of perceived exertion (RPE), which evaluate the subjective exhaustiveness perceived by users after working out. For active older adults, it is recommended to exert at intensities between 5 and 8 in a 0 to 10 scale of RPE (e.g., Borg, OMNI) [35]. Unfortunately, only 27.1 % of adults aged 75 and older meet the recommended amount of cardiovascular training and only 8.7 % report engaging in the recommended physical activity[1] levels.

1.2.2 Human-Centered Exergame Design

In the HCI field, one of the most used methods for designing highly contextualized, personalized, usable and useful interactive systems is the human-centered design approach [38]. Through this method, the system's final user is involved in all steps of the design and development process, thus guaranteeing a solid understanding of users' needs and motivations as well as providing the possibility to keep the solutions in a constant state of dynamic iteration. Human-centered design has been used to inquire about the benefits and barriers of older adults in playing videogames [39], [40], gaming preferences, personalities and motivators [41], [42], in the design of user-oriented Exergames for fitness promotion [43], for gamifying systems for children's nutrition and fitness education [44], and for entertainment [45].

Research has shown that senior populations are widely different from young adults regarding game preferences concerning playability, challenges, and motivators [46]. Moreover, through techniques such as focus groups, perspectives, and perceptions towards videogames have been disentangled, highlighting the importance of perceived benefits, difficulty and relevance for engaging with new technologies [47]. Since Exergames' personalization has been reported as one of the major bottlenecks in

[1] https://health.gov/paguidelines/second-edition/report.aspx

probing the effectiveness of this technology applied to seniors [22], the use of participatory and inclusive design methodologies can facilitate technology adoption. Indeed, multiple researchers have identified the human-centered design approach as adequate and preferable for the design of compelling, useful and usable Exergames for exercise promotion [43], [48]. For instance, Uzor and colleagues demonstrated how empowering seniors with design tools and techniques could boost the likelihood to create enjoyable rehabilitation tools for falls prevention [49]. Participants were modeled using Personas, facilitating the understanding and communication of characteristics and needs [38][50]. The fact that senior adults tend to show deficient levels of technology literacy and videogame experience must also be considered [51], [52]. This presents an exciting challenge and opportunity to develop novel assistive technology for the older population [53]. Because older people have few or no past experiences with videogames, starting a design process by inquiring about preferred videogame mechanics, aesthetics or technologies is not the most adequate. Multifaceted and participatory approaches have been widely recommended by physicians and sports scientists, stressing the need for clearly defining an appropriated fit of game design elements for each target group [13]. For that, we should know the standardized tools and assessments used to measure overall fitness statuses in older adults. Therefore, next, we highlight the most widely recognized guidelines described by sports scientists and physiologists to assess functional fitness in older adults.

1.2.3 Long-term interventions with Exergames

Longitudinal studies provide an excellent method to track participants' evolution under Exergaming programs, facilitating the determination of any associated change in physical parameters as well as inquiry in the game user experience. Recent reviews in Exergames promoting physical activity in older adults emphasize the need for additional and better-designed studies which assess the validity and long-term adherence of custom made Exergames [11] [54]. The literature shows promising examples of longitudinal interventions that use various protocols to evaluate the impact of Exergames in physical and cognitive domains.

Studies focused on physical activity performance

Chuang reported a 3-months study and colleagues [55] who investigated the effects of virtual reality (VR) enhanced exercise protocol in older patients undergoing coronary artery bypass grafting. Twenty subjects followed an aerobic exercise protocol with training sessions lasting 30 minutes twice per week, completing 20 training sessions in total. Older adults were divided into two groups; one of them included the VR-enhanced Exergaming and the other was used as a control. The Exergaming condition used wraparound screens to simulate virtual environments while users were on a treadmill [56]. Results showed that subjects at the VR-enhanced Exergaming condition reached more quickly the recommended levels of physical exertion as described by target metabolic cost, target oxygen consumption and target heart rate than subjects in the control condition. These achievements led to a more adequate and quick therapeutic process accelerating the maximum recovery of the cardiovascular function.

Similarly, long-term care residents were exposed to an 8-week program intervention consisting of X-Box Kinect based Exergaming sessions of 35 minutes twice per week [14]. The Exergame sessions were supplementary to any other physical activity participants were attending. Users in the control condition continued their usual activities and participated in any physical activity that was generally non weight-bearing of low intensity. 86 older adults participated in a multi-center study. Both groups (control and Exergaming) showed improvements in user's mobility as measured by pre and posttests analysis of standardized mobility tests and data from activity trackers. There were no significant differences between the groups for any of the variables assessed in mobility. Authors reported 55% of attendance for the scheduled Exergaming sessions.

Studies revealing the cognitive and physical benefits of Exergaming
In a review paper published in 2017, a total of six Exergaming studies lasting 12 weeks or longer demonstrated having moderately-to-large effects on participant's cognitive functions, thus illustrating the potential of using Exergames to enhance user's mental wellbeing [57]. Three longitudinal interventions quantified the impact of Exergames on specific cognitive functions of older adults. First, physical and cognitive functions in a group of 32 independently living older adults were assessed in a pretest-training-posttest experiment using Exergames from the Nintendo Wii console. The study was 14 weeks long including assessments and participants completed a 24x1 hour Exergaming training sessions (twice per week). As a control condition, the researchers used a group of older adults without any treatment. Batteries of neuropsychological and functional fitness tests were applied to measure the Exergaming effects. After the training regime subjects showed improvements in cognitive functions such as executive control and processing speed.
Additionally, the functional fitness test revealed improvements in muscular strength (lower and upper limbs), balance and cardiovascular components. Flexibility did not show statistical significance in the follow-up assessment [58]. The second study evaluated the effects on cognitive well-being in a 3-months long, multi-site cluster randomized control trial that included 63 mentally healthy older adults from retirement communities [9]. Researchers used VR cycling as Exergaming sessions that were compared with conventional exercise in stationary bikes. Both groups were instructed to gradually increase exercise frequency to 45 minutes per session, five times per week. Results exhibited a 23% relative risk reduction in clinical progression to mild cognitive impairment in the Exergaming condition when compared to conventional exercise. Besides, neuroplasticity was measured through biomarker analysis (Brain-Derived Neurotropic Growth Factor Results - BDNF) showing that cybercyclists experienced greater increases than traditional exercise.

Finally, Eggenberger and colleagues used a combined program consisting in dancing Exergaming with strength and balance exercises during six months (52 sessions in total) to measure cognitive performance in healthy older adults [59]. Training sessions consisted of 20 minutes of aerobic training (Exergaming, treadmill with memory tasks, treadmill walking) and 40 minutes of complementary strength and balance exercises. The training frequency was twice per week with a duration of around 1 hour. Results suggested the efficacy of multicomponent training (physical-cognitive) that includes Exergaming in boosting particular executive functions such as shifting attention and working memory. Mainly, cognitive performance was maintained until the 1-year follow-up, which included executive functions, long-term visual memory (episodic memory) and processing speed. Furthermore, the conditions associated with cognitive training (Exergaming and treadmill with memory tasks) showed advantages in dual-task gait, functional fitness and the reduction of fall frequency once compared with the treadmill walking condition [60].

Studies on game user experience
Other studies present efforts towards analyzing different aspects of game user experiences during long-term Exergaming interventions. Kappen and colleagues carried out an 8-weeks intervention with gamified, non-gamified and control exercise conditions finding that the motivation, enjoyment, and engagement were higher in the gamified group [61] compared against the rest. Likewise, Uzor and colleagues compared booklet-driven exercise programs versus Exergames in a 12-week program that aimed at encouraging adherence to a home-based fall prevention program in older adults [19]. Results revealed a greater exercise program adherence and confidence against falling for the Exergaming program when compared with the booklet-driven counterpart. Beyond that, Exergames were scored as highly usable following the system usability scale.

Furthermore, a qualitative inquiry approach was used to investigate the effects of Exergames in a 3-month intervention in two senior care facilities [62]. Custom-designed games were combined with commercially-grade Exergames in a weekly exercise session with 12 older adults. Results suggested that playing Exergames constituted an enjoyable and empowering experience towards the promotion of seniors' independence.

To improve the understanding of the health benefits associated with training programs that use Exergames, researchers have been also using physiological sensing to unveil to what extent Exergames are effective in promoting measurable changes.

1.2.4 Physiological signals and Exergames

Our bodies are compounded by interrelated biological systems that are continually changing and manifesting our behaviors, emotions, and responses in several physical and physiological manners. While interacting with Exergames, our sweat glands in many parts of the body change their composition, the heart beats are regularly adjusting their pace to better bump blood following exercise demands and our rate of breathing changes in response to any elicited emotion [63]. These examples are just a few of the body metrics that can be measured during playful experiences and used to understand players' behaviors better. Psychophysiological research is described as an experimental method in which physiological measures are used as dependent variables and psychological states as an independent [64]. Psychophysiology has been widely used to study user's behaviors during videogame-mediated experiences [65]. While conventional game metrics such as self-reports, surveys, and user observation provide insights on the experience of players, they can miss emotional responses [66]. These can be apparent responses but also non-apparent such as body posture, facial expression or psychophysiological changes. The latter ones are not visible to the naked eye and require specific biomedical equipment to measure signals such as electrocardiography (ECG), electromyography (EMG), electroencephalography (EEG) or electrodermal activity (EDA) [67], to mention a few.

Overall, physiological sensing has been extensively used as a passive technique to record human responses while interacting with Exergames However, those signals have also been utilized to augment the interaction by modulating Exergame variables in response to any human state detected. Next, we describe the use of physiological sensing for both passive and active (or reactive) manner in the Exergaming context.

Game user research (GUR)

From a practical point of view, game user research (GUR) studies the whole experience players have with a game: from the initial interaction with the user interface until any emotion elicited during and after gameplay [63]. Although many research methods can be strictly used to study GUR, physiological sensing has been gaining attraction as a complementary tool to describe players' behaviors [65]. There are three main advantages of using physiological metrics in GUR: i) they are more objective and direct compared to conventional methods because they are language independent and do not rely on memory; ii) they can be covertly assessed continuously, without interfering with the interaction, thus providing a high level of temporal precision (useful to detect event-related responses) [65]; and iii) they can detect unconscious emotional and attentional responses [68]. However, there is no substantial evidence on how gaming elements affect physiological signals and how systems themselves can be designed to anticipate undesirable states such as frustration, boredom or fatigue. Notably, the use of psychophysiological methods to study Exergame experiences has limitations related to signal acquisition and data processing during exercise performance [30].

Nevertheless, the use of physiological sensors to measure exertion is not new [69]. The analysis of multiple body changes that, to some extent, reflect user's behavioral states emerged as a powerful tool for quantitative GUR. In this case, the regulation of emotions is assessed by measuring the activity of sympathetic (fight and flight reactions) and parasympathetic (rest and digest reactions) nervous systems [70].

Several studies reported on the use of physiological measurements during Exergaming [10], [71], [72]. Some authors have focused on quantifying behavior using a set of domain-specific features [73], allowing the comparison of physiological changes induced by Exergaming in different populations [74]. For instance, Graves et al. [75] found that energy expenditure (EE) and heart rate (HR) during commercial Exergame (Wii Fit) activities were higher than during conventional handheld videogames; but lower than during treadmill exercise in adolescents, young and older adults. McGuire et al. [76] showed that physiological responses (HR, EE, and ventilation) are higher during multiplayer Exergame experiences than during conventional modes. Other studies revealed that heart responses to Exergames could be larger than those elicited by conventional physical exercises [77]. EDA has also been widely used as a measure of arousal in GUR [65] and for monitoring sympathetic modulation during exercise [78]. One study analyzed EDA responses for fatigue detection during Exergaming and identified that the basal skin conductance decreased with fatigue [79]. HRV metrics have also been used to quantify the impact regarding cardiovascular regulation of Exergames with stationary bikes (cyber-cycling), demonstrating the accuracy of heart rate variability (HRV) metrics to precisely describe body-brain interrelations in Exergaming [80]. Less conventional approaches to measuring physiological responses in Exergaming interventions have used EEG to quantify the complementary cognitive impact of exercising with Exergames [81] as well as functional spectroscopy (fNIRS) to unveil the cognitive modulation produced by game difficulty [82]. Those findings are now providing concrete evidence towards the creation of novel neuroplastic hypothesis about cognitive improvements produced by the so-called Neuro-Exergaming approaches [83], [84].

Hence, developing a better understanding of the psychophysiological responses to Exergaming can be a central element to improve the assessment of users' behavior during gameplay providing more suitable exercises session after session. Particularly interesting would be imagining applications in the front-end of the system, this is: what to do after detecting the human state? How can the system assist users based on their levels of fatigue or frustration? To what extent can this intelligence persuade users to stay in a desirable state?

Biocybernetic adaptation

Maybe the most sophisticated way of using physiological signals in gaming contexts is by allowing game mechanics to be paced or modulated by detected human states (physical or cognitive). This requires an active pipeline of the collection, analysis, and translation with physiological signals that are transformed in adaptation mechanisms in the so-called biocybernetic loop (BL) construct [29], [85]. As an adaptive mechanism, BLs should first collect signals from the users via physiological sensors, analyze and process them to extract meaningful information regarding user's psychophysiological states (e.g., workload, stress, cardiorespiratory behavior) to finally translate it in a control output signal [85]. Within this collection, analysis, translation model, complex stages of signal processing, user modeling, and decision making have to be carefully designed and carried out to guarantee a functional and efficient real-time adaptation loop.

BLs have been used in HCI as an intelligent adaptation mechanism that empowers interactive systems with a physiologically-aware layer able to augment the asymmetrical relationship between human capabilities and information flow [86]. For example, from the early assistive and cognitively automatized flight control system developed at NASA Langley [87], various adaptive systems have been proposed to improve music learning processes through adaptive interfaces based on neurophysiological measurements [88], release scents by means of modulating intensities and frequencies in an olfactory-wearable device [89], and enhance audience engagement in a virtual simulation of an artistic performance [90].

Interestingly, videogames and virtual reality (VR) simulations have used BLs to improve crucial psychological parameters such as stress, enjoyment and flow aiming at improving the game user experience overall [91]. Remarkable studies with games include the creation of a brainwave modulated arcade game that adjusts the level of game demand based on a psychophysiological model of players' engagement [92] and a physiologically adaptive car-racing game that used a PID (proportional, integrative, derivative) controller to adapt game variables such as car speed, road visibility and steering jitter based on players' arousal levels [93]. Regardless the increasing popularity of BLs among game developers, game user researchers and technologists [29], its implementation still faces several limitations regarding the communication with popular game engines, integration of multiple physiological signals [94], and the construction of the adaptive rules [95]. In the last decade the possibility of using the BL technology in videogames was introduced [29], and more particularly, Exergames were adopted as a case scenario [96]. The idea behind the physiological computing construct is that by modulating the game variables through detected psychophysiological states (e.g., engagement, stress, frustration, and fatigue), essential self-regulation skills can be trained, thus boosting the health benefits of Exergaming.

1.2.5 Cardio-Adaptive Exergaming and the Dual Flow Model

The dual flow model is a framework that integrates psychophysiological responses in Exergaming in two different dimensions of the exercise: attractiveness and effectiveness [97]. Attractiveness can be modeled by the well-known flow model from Csikszentmihalyi that balanced user's skills with the perceived challenge [98]. The second dimension, effectiveness, relates to the physiological responses to exercise in order to adjust the intensity of the exercise with the actual user fitness. The most extended approach used to improve effectiveness with physiological adaptation in Exergaming has been demonstrated in applications modulated by cardiac signals using the concept of a target HR. In cardiorespiratory fitness (CRF) and following the ACSM guidelines [37], it means to increase and maintain the HR levels in the target HR zone in which the health benefits of the training can be maximized [99]. The target HR zone relates to the exercise intensity and is defined as a percentage of the heart rate reserve (HRR) - which is the difference between the maximum HR (HR_{max}) and the HR during resting (HR_{rest}) - as expressed in equation 1:

$$targetHR = [\%\ exercise\ intensity * (HR_{max} - HR_{rest})] + HR_{rest} \quad (1)$$

Following the target HR approach, a study with 20 young participants evaluated the effectiveness of using a game mechanic called HR-power-ups to encourage more vigorous play in an exergaming intervention [100]. The mechanic consists of providing in-game rewards to players when they reach the appropriate target HR level of exertion. For instance, an avatar may have a stronger attack or change the appearance. Players seated in a cyber-cycling setup wore a Garmin heart rate monitor and used a game controller to control the avatar's direction and launch special abilities. The pedaling pace was used to control the avatar's movement. The study concluded that by using HR-power-ups during 5 minutes of training, players improved exertion levels leading to increases in time over the target HR zone from 50% to 100% [101] when compared with a non-adaptive version of the exergame. The approach was extended to convert off-the-shelf videogames into exergames. Preliminary results showed that this transformation did not affect the players' enjoyment while the HR levels fell slightly below fitness recommendations [102]. These approaches emerged from a mismatch between player-centric models for Exergames and physical demands [103].

In the effectiveness domain, a PID controller was applied to keep players exerting in the desired target HR zone. Results demonstrated that the use of a PID control loop was very successful in helping players to maintain desired exertion levels for a well-structured workout. Two additional studies have used HR-based adaptation in exergames for children. The first used a modular mobile exergaming system to prevent obesity via using a smart insole [104]. The exergame encouraged players to keep up with a flying cow by adjusting their stepping pace. The adaptation used the HRR formula (see equation 1) and modulated the frequency of appearance of obstacles, thus affecting the pace of players. A pilot lab study with two children showed the effectiveness of the mobile system to push players to reach the target HR threshold. Finally, Martin-Niedecken and colleagues [105] developed a dynamically adaptive fitness exergame for children and young adolescents. The system used the Kinect (Microsoft, Washington, USA) and Polar H7 sensors to register the movement and HR, respectively. The exergame can be played through a haptic feedback setup that demands coordination and spatial orientation skills. Although the adaptation of the exergame parameters was made manually according to the HR levels, results showed that young players worked-out within the desired fitness zones [105].

To summarize the application of biocybernetic adaptation in Exergames through cardiorespiratory variables, we conclude that:

- Studies with older adults are scarce, hiding the potential effects of this technology to optimize exercise performance in this population.
- Comparisons with control conditions are not commonly used, making the advantages of using this technology against conventional training methods unknown.
- Experiment replicability is challenging due to the complexity of the setups, cost of the sensors, the unavailability of the systems, and the specialized knowledge required.
- There is a lack of field experiments, confining the use of biocybernetic adaptation to laboratory studies.
- Most of the studies evaluated the use of BLs in short time periods (less than 10 minutes), which do not adequately reflect realistic or recommended times for cardiorespiratory training.

1.2.6 The lack of specialized and accessible software tools for physiological computing

Although the convergence between gaming and physiological computing technologies has risen expectations in both bioengineering and game design fields, the lack of specialized, easy-to-use and accessible software tools to integrate physiological signals in interactive applications have limited this synergy [29], [106], [107]. From one side, although there are several tools for post-processing of physiological signals, some of the limitations presented by the state-of-the-art toolboxes are: the cost associated with licensing, the generality of the scope (which limits the specificity of their signal processing methods), the lack of graphical interfaces for their operability, and the absence of techniques to facilitate data interpretation (see *Table 1*) [108]. On the other side, the development of BLs has been advanced by academia mainly for research purposes [29]. Although BLs enable the creation of genuine intelligent systems that use implicit task-context and user-intention information [85], the creation of such systems is inherently complex. As a result, the final biocybernetic systems are mostly custom-built and respond to a single-task adaptation mechanism, which makes it difficult to replicate or generalize to other applications [29]. This impedes researchers and developers to design, construct, iterate rapidly and validated new prototypes (see *Table 2*) [94]. Next, we describe the current status of the software tools available for both post and real-time processing of physiological signals that allow us to better position our contributions regarding the available state-of-the-art toolkits.

Multimodal physiological toolboxes for post-processing

We reviewed the available toolboxes for multimodal physiological signal processing. Interestingly, we found a list of 7 different software tools available to the community, which can be used to process data from several physiological signals (see). Three of the toolboxes are mainly used with their respective hardware kits and have a business model. Firstly, the Acqknowledge [109] provides support for processing a wide range of physiological signals such as EEG, EMG, EDA, electrooculography (EOG), electroglottographic (EGG), and ECG. The toolbox is offered in combination with the BIOPAC biosignal devices and performs tasks from data acquisition to modeling using a simplistic guide user interface (GUI) with menus and dialogs. Similarly, the g.BSanalyze [110] is a software tool which can perform offline biosignal data analysis under the Matlab environment or standalone. This software has been extensively used for the brain-computer interface (BCI) community in conjunction with the EEG hardware produced in the same company. The toolbox integrates specialized functions to visualize neurophysiological signals and includes many biosignal datasets of multiple BCI paradigms. The last software with a paid license is the OpenSignals [111] which uses data processing modules as optional add-ons of a free signal visualization core tool. The core functionality embraces data acquisition and data visualization, and the add-ons are for HRV and EMG data analysis. Likewise, the ANSLAB uses a mix-model to commercialize a software created to research in psychophysiology comprising ECG, EMG, EDA, PPG, and other cardiorespiratory signals [112]. Two software tools that do not include GUIs are the Biosig Project [113] and the TEAP (Toolbox for Emotional feature extraction from Physiological signals) [107]. The first incorporates a large list of open source libraries wrote in C, C++, Matlab and Octave and methods for signal processing, feature extraction, and classification. The TEAP is a toolbox oriented for affective computing applications covering analysis for EEG, ECG and EDA signals. Finally, the Augsburg Biosignal Toolbox [114] comes along with a GUI, which facilitates the processing of multiple physiological signals for extracting features, automatically select the most relevant ones, and use them to train classifiers.

Software tools to create Biocybernetic Loops

Some software tools have emerged in the last decade to facilitate the creation of BLs and spread the use of physiological adaptation for multiple purposes. One well-known example is the OpenViBE software platform [115], an open-source tool created to support brain-computer interface (BCI) experiments. Using a modular, flexible and simplistic architecture, OpenViBE has been successfully used in closed-loop systems for assistive technology such as spellers, as well as for BCI videogames and VR simulations [116], [117]. Although OpenViBE has been mainly used for BCI applications, studies using ECG data for tangible interfaces [118] showed the potential of the software besides neurophysiological signals. The FlyLoop framework [119] is a small and lightweight approach in Java that enables programmers to develop and experiment with physiologically intelligent systems rapidly. The system is presented as a tool to improve decision-making in workload detection via wearable biosensors. Comprising of a set of four modules (data sources, filters, learners, and outputs), the framework is designed to provide reproducibility and accessibility to non-programmer users. Finally, the Neuromore platform was initially designed as a flexible tool to create novel biofeedback visualizations [120] [121]. Nowadays the tool is presented as a development platform for interactive applications which can combine real-time physiological data and machine intelligence to create BLs. Focused on the use of wearable and low-cost BCI systems, Neuromore combines multiple technologies to connect commercial-grade physiological sensors with visual scripting. It can process data and classify it regarding states of mind such as focus, relaxation, flow, creativity or concentration. Unfortunately, the software is still in early stages and the integration with game engines is still unclear.
Similarly, Neuropype (Intheon Labs, San Diego) allows interfacing diverse sensors (EEG, motion capture and eye tracking) and includes more than 200 algorithms for artifact removal, filtering, 3D mapping, connectivity analysis, brain state classification among others. Neuropype includes an open-source drag-and-drop visual dataflow programming environment called Pipeline Designer to allow linking in real-time data visualizations and BL' pipelines. Finally, a tangible LEGO-like approach to interactive wearable computing was created to empower children in a participatory design process. The *MakeWear* approach includes wearable sensors to measure physiological signals such as heart rate and physical movement, and it integrates a visual language module based on Blockly (Google, California, USA) to create adaptive rules. Actions that translate signals into perceptual forms include sounds, lights, and vibrations using small electronic actuators [122]. Similar approaches have used the combination of simplistic programming languages with wearable sensors to provide hands-on educational activities in the physiological computing field [123]. Interestingly, all of the above-mentioned software tools use visual language scripting techniques to simplify the construction process of BLs.

2 Research Approach

This section describes the research approach followed in this thesis by describing the research questions that motivated our investigation process. Consistently, it summarizes our research contributions that aimed at providing insights into the research questions detailing each of the tools developed and its importance, the main findings of our studies as well as the current plans for the technologies here developed.

2.1 Research Questions

After reviewing and analyzing the novel approaches to enhance the health benefits of using Exergames for exercise promotion in the older population as well as the current limitations of using them outside research labs, this thesis aims at investigating on two fundamental research questions:

Research Question 1: How can human-centered design approaches be integrated into the creation of effective and contextually rich Exergames to promote exercise in seniors?

Human-centered design is based on a careful observation and modeling process of the target population in their natural and daily environment. Although very used in software engineering process, its use in Exergame design for seniors has been scarce, and the validation of the associated potential health benefits rarely quantified in the long-term. Therefore, this research question was established to explore whether human-centered design approaches can be useful to deliver enjoyable and effective fitness training based on Exergaming.

Research Question 2: How can the Biocybernetic Loop construct provide a suitable solution to enhance the cardiorespiratory benefits of Exergaming?

This research question covers the *why* and *how* the biocybernetic loop construct can be effectively used to enhance the cognitive, functional fitness, cardiovascular regulation, and user experience benefits of aerobic training with Exergaming. We are also interested in the development of physiological computing software tools that can foster the synergy between Exergaming and applied biocybernetic research.

2.2 Research Contributions

Currently, many theoretical and experimental approaches have been contemplated to improve Exergaming effectiveness in active and healthy older adults. Nevertheless, commercially available and poorly designed Exergames are still the order of the day, which are mostly evaluated during short-term and uncontrolled research trials that often ignore important standardized fitness recommendations [11], [18], [124]. Additionally, novel physiological adaptive technologies that have been showing very promising scientific evidence for enhancing healthcare benefits of Exergaming [96],

[100], [125] are rarely applied with older adults and very restricted to specialized research labs. Thus, the impact of Exergames that used sophisticated (e.g., physiological adaptation) and more participative (e.g. human-centered) HCI methodologies is still underexplored.

This research aims at promoting the adoption of highly adaptive and customizable Exergames that i) include physiological computing strategies using a freely available software tool for adding biocybernetic adaptation; and ii) have been designed with contextual information from Portuguese older adults and were evaluated with standardized fitness guidelines in two longitudinal interventions. To summarize, this thesis encloses a unique set of research contributions in the fields of Exergaming, physiological computing, and human-centered game design.

A. A set of software tools for physiological computing have been designed, developed and made freely available (Chapter 3):
    - Physiolab for physiological signal post-processing
    - Cardiorespiratory Radar Plots to aid data interpretation in fitness assessment contexts via HRV metrics.
    - Biocybernetic Loop Engine to facilitate the incorporation of physiological adaptation in videogames.

B. Four Exergames were designed, developed and validated by following an iterative human-centered design process (Chapters 4 and 5) which:
    - Constitute concise scientific evidence for multidisciplinary and participatory Exergame design.
    - Support physical activity in older adults aligned with international recommendations on multidimensional training (ACSM) using a highly personalized solution.

C. A physiological adaptation technique was used as a system intelligent layer in an Exergame for cardiorespiratory exercise in older adults (Chapter 6) which:
    - Unveils the effectiveness of biocybernetic adaptation in improving cardiovascular performance during Exergaming.
    - Exposes new evidence of physical and cognitive benefits of Exergames enhanced with biocybernetic loops.

Besides, around 150 older adults from local senior gymnasiums were positively impacted by means of exercising through our technologies, which established a solid base for further collaborations. Two systems have been permanently installed in the senior facilities and future interventions are being planned to complement the research findings documented along this research.

3 Software Tools for Physiological Computing

In this chapter, we describe three different physiological computing tools that are freely accessible and have been extensively used along this thesis: a software toolbox for signal post-processing (PhysioLab), a novel data visualization technique (cardiorespiratory radar plots), and a real-time engine to design and prototype physiologically adaptive videogames (Biocybernetic Loop Engine). We highlight the main features of each tool, showing scenarios where the software tools are complementarily used with conventional fitness assessment techniques, and we also describe our efforts towards promoting the use of our integrated tools.

The goal of this chapter is to describe our efforts towards creating two software tools and one visualization method for physiological computing, which can be used by researchers, game designers/developers and technology enthusiasts. Section 3.1 describes PhysioLab, a post-processing multivariate Matlab-based toolbox created to aid the data analysis of three physiological signals: ECG, EMG, and EDA. A novel data visualization technique is referred to in section 3.2, which used normative data to create a contextualized radar plot with CRF and HRV computed parameters from PhysioLab. Finally, section 3.3 documents the design and implementation process of the Biocybernetic Loop Engine (BL Engine), an interactive software tool created to integrate physiological adaptation using BLs in videogames.

3.1 PhysioLab: A multivariate physiological computing toolbox for ECG, EMG and EDA post-processing signal analysis[2]

PhysioLab is a physiological computing toolbox developed to support the analysis of ECG, EMG and EDA signals, and facilitate data interpretation with a focus in the fitness assessment domain [108]. The toolbox integrates multiple widely used algorithms with normative data for signal pre-processing and feature extraction. PhysioLab has been developed using Matlab release 2013a (MathWorks Inc., Massachusetts, US). The toolbox is freely available at http://neurorehabilitation.m-iti.org/tools/physiolab. The software tool was extensively used for physiological data post-processing in the studies reported at chapter 6.

3.1.1 Input data and compatibility

PhysioLab can import data files from different low-cost physiological sensors such as Bitalino, Biosignal-Plux, e-Health Kit or Myo Armband, exported from their native software packages [126], [127]. Further, to allow the easy integration with other technologies, a "Load from Workspace" option enables loading any physiological data available from the Matlab Workspace

[2] Part of the content of this chapter was published at: J. E. Muñoz, E. R. Gouveia, M. S. Cameirão, and S. B. i Badia, "PhysioLab-a multivariate physiological computing toolbox for ECG, EMG and EDA signals: a case of study of cardiorespiratory fitness assessment in the elderly population," Multimed. Tools Appl., pp. 1–26, 2017.

organized as column vectors. This option is extremely useful if a user wants to manually pre-process the data or extend the analysis with methods not included in PhysioLab. Additionally, the software provides the option to select a specific time-based Region of Interest (ROI) from the signals. Finally, using the option "Save in Workspace" the user can export the processed data from PhysioLab and make it available in the Matlab workspace for further analysis.

3.1.2 User Interface

PhysioLab is entirely operated using a graphical user interface, which is divided into three parts: a) Analysis Panel, b) Signal Visualization Panel, and c) Feature Extraction Panel (*Figure 1*).

a. Analysis Panel: this panel includes the three physiological signals supported at this stage by PhysioLab: EMG, ECG, and EDA. The signal to be depicted in the GUI should be selected. In this panel, users can customize some parameters used for the analysis in order to adjust the algorithms, thus improving the accuracy of feature extraction. For EMG signals, time and frequency domains are included. ECG signal analysis is based on R-peak detection. The analysis includes HR, HRV variables (in the time and frequency domains) and the estimation of VO2max. EDA signals are processed and divided into tonic and phasic components, representing the slow and fast behavior of the skin conductance. This panel also includes an option to personalize the range of the data to be analyzed by predefining signal windows or ROIs before starting the analysis.
b. Signal Visualization Panel: this section contains multiple representations of the processed signal to visualize the processing results and adjust the analysis dynamically. The signal to be depicted in this panel is selected in the analysis panel. Particularly, the top window displays the raw data, and the lower-left window plots the first category of processing (time for EMG, R-Peak analysis for ECG, and tonic responses for EDA). Similarly, second category features (frequency for EMG, HRV for ECG, and phasic responses for EDA) are displayed in the lower-right panel to complement and ease the comparison between categories. The extracted features such as ECG waveform and detected R-Peaks, linear EMG envelope and normalized EDA signals are plotted superimposed with the processed data to facilitate visual inspection of the results. Additionally, by selecting the "Separate Plot" option, plots can be created in separate pop-up windows facilitating the data visualization.
c. Feature Panel: the bottom panel contains a number of divisions to display the values of the features extracted from each signal using the international system of units. As in the previous panel, left and right side boxes display the first and second category of features, respectively.

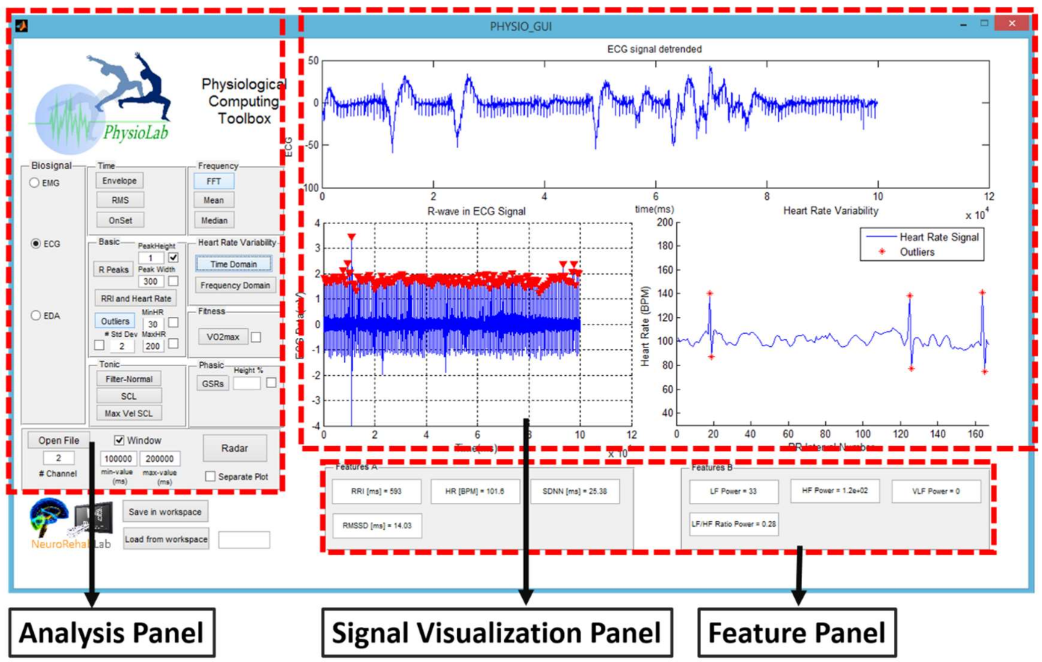

Figure 1. The graphical user interface of PhysioLab is divided in three parts: 1) Analysis Panel, 2) Signal Visualization, and 3) Feature Extraction panel.

3.1.3 Feature Extraction

Electromyography (EMG) signals

PhysioLab supports the analysis of the EMG data and its processing in time and frequency domains. In physiological recordings, the presence of trends - slow and gradual changes in some properties over complete recordings - are common. Hence, the EMG signals are initially detrended by subtracting a moving average. This technique is always desirable to improve the reliability of the signal to describe complex physiological phenomena and improve the diagnoses [128]. Subsequently, the signals are full-wave rectified and low-pass filtered following standard recommendations for EMG processing (cutoff frequencies below 20 Hz) [129]. PhysioLab uses 20 Hz by default.

<u>The time domain</u> parameters included in PhysioLab are the linear envelope (LE), which has been assumed to be linearly associated with the force under isometric conditions and non-linear under isotonic conditions [130]; the Root-Mean-Square (RMS) amplitude which are associated with physiological descriptors of motor units behavior, such as muscle fatigue [129].

EMG frequency analysis can also provide both physiological and non-physiological information of the signal. Specifically, the non-physiological information reveals the presence of artifacts and noise contamination from different sources such as electrical interference [129]. Physiologically, EMG frequency analysis is usually associated with fatigue analysis [131]. A Fast Fourier Transform is used to compute the power spectrum density (PSD), which for normal human muscles with surface EMG is between 20 Hz and 450 Hz [132]. Muscle fatigue alters the spectral information by changing the shape of the action potentials of muscle fibers, decreasing the amplitude and increasing the duration [132]. Hence, as fatigue progresses, there is a shift of power towards lower frequencies.

The frequency domain parameters included are the Mean Frequency (MNF) and the Median Frequency (MDF) which can widely describe the fatigue phenomena in a more reliable way than any time domain parameter [131].

Electrocardiography (ECG) signals
ECG processing in PhysioLab is based mostly on HR time domain features. First, the original ECG signal is fitted with a low order polynomial ($n < 10$), which is then used to detrend it. Some muscle tremors (voluntary or involuntary) are unavoidable [133] and produce EMG activity with amplitudes and frequencies 0.1-1 mV and 5Hz- 1 kHz, respectively, that partly overlap with the ECG signal. This induces in ECG a baseline wander effect that can mask important information. Thus, the ECG signal is smoothed by a fifth order Savitzky-Golay FIR filter. To extract HR information, each heartbeat waveform is analyzed, and R-peaks detection is carried out using a threshold based on peak morphology analysis [134]. PhysioLab presents both the original and detrended signals after the R-peak detection, in case the user needs to perform manual adjustments of the thresholds in order to improve the accuracy of the R-to-R (RRI) interval detection. Additionally, the user can manually adjust the temporal and amplitude thresholds (R-peak's height and width). Once the R-peaks are extracted, both heart rate variability (HRV) and heart rate (HR) can be computed from the RRI information.

Time domain parameters for HRV analysis are included in PhysioLab by means of computing the mean value of normal R-to-R intervals (mRRI), the standard deviation of the RRI (SDNN) which is a global index that reflects cardiac resilience [135], and the RMS value of successive RRI data (also called RMSSD) which reflects the parasympathetic regulation of the autonomic nervous system [136].

PhysioLab also computes frequency domain HRV parameters using a Welch's PSD estimation with a Hanning window to estimate the HRV spectrum [137].

Frequency domain parameters for HRV analysis are included by computing the high (0.15-0.4 Hz), low (0.04-0.15 Hz) and very low (0.003-0.04 Hz) frequency band powers that are closely associated with the modulation of both branches of the autonomic nervous system [135].

Finally, another important factor to evaluate functional cardiorespiratory capacity is $VO2_{max}$. $VO2_{max}$ is the maximum oxygen uptake capacity and it has been shown to be a reliable measure reflecting the functional capacity of the cardiorespiratory system [6]. We estimate VO_{2max} by performing the ratio between the heart rate values at rest (HR_{rest}) and maximal exercise (HR_{max}). The value of HR_{rest} is defined as the lowest value of any 1-min average during a 5-min sampling period, and the HR_{max} is approximated using the highest 5-s average during different exercise tests, like step or treadmill tests [6]. Additionally, when ECG data for HR_{max} is missing, PhysioLab approximates it through the widely accepted formula by Tanaka [138], which is an age-dependent model to compute HR_{max}. $VO2_{max}$ is widely used to classify CRF performance (poor, fair, good, excellent or superior) using age and gender-specific normative tables [6].

Electrodermal Activity (EDA)
The analysis of the EDA signal can be split into tonic and phasic components. The Skin Conductance Level (SCL) or Tonic Level denotes the baseline or resting level of the EDA signal. SCL is known to relate to sweat gland activity [139] and is measured in microSiemens (µS). Galvanic Skin Responses (GSRs) or Phasic Changes are noticeable episodes of sudden increases of conductance caused by purely sympathetic arousal generally generated by an external stimulus. The level of GSRs is thought to be an accurate indicator of the degree of arousal caused by the stimuli [139].
To eliminate high-frequency noise, an 8th order low-pass filter with a cut-off frequency fc = 15 Hz is applied. This allows the reduction of false positives in the detection of phasic events, which do not demand high-frequency responses [47,24]. Then, in order to minimize the impact of overlapping (superimposed) GSRs, we implemented a solution based on deconvolution techniques to decompose EDA into its tonic and phasic components. Subsequently, with the purpose of facilitating the comparison of EDA signals from different users, PhysioLab normalizes the EDA data following the formula proposed by Cacioppo and colleagues [70].

GSRs detection is carried out based on a minimal distance between consecutive GSRs (set as 4 seconds) and a minimum amplitude (in %) threshold provided by the user (default value = 30 %) [70]. Based on response latencies to stimuli, it is common to use a 1-4 seconds latency window. Hence, any GSR that begins between 1 and 4 seconds following the stimulus onset is generally considered to be elicited by that stimulus [49]. GSRs that are not elicited by a stimulus are referred to as spontaneous or nonspecific GSR (NS-GSRs). PhysioLab presents the different steps of the EDA feature extraction process in the signal visualization panel: raw data, filtered and normalized EDA data, and superimposed GSR detection with temporal labels. Additionally, the mean value of SCL and max value of SCL velocity are extracted and displayed in the Features Panel, jointly with the SCL curve, superimposed to the raw data plot.

3.1.4 Software tool positioning

After introducing the features of the PhysioLab toolbox, *Table 1* presents a comparative analysis that allows a precise positioning of our tool in regards to ones previously developed and mentioned. Here, we highlighted the specific scope (e.g., fitness assessment) and the open source and data interpretation features of PhysioLab.

Table 1. Relevant multimodal physiological toolboxes for signal post-processing and visualization. ECG: Electrocardiography, EDA: Electrodermal Activity, EEG: Electroencephalography, EMG: Electromyography, EOG: Electrooculography, Resp: Respiration, ICG: Impedance Cardiography, ECoG: ElectroCorticography

Software Tool	Signals Supported	Scope	First Release Date	GUI	License	Studies	Functionality
Acqknowledge	ECG, EDA, EEG, EGG, EMG and EOG	General Purposes	1993	Yes	Paid	> 10	Data acquisition, signal filtering, artifact processing, feature extraction, classification, and modeling.
g.BSanalyze	EEG, ECG	General Purposes	2004	Yes	Paid	> 10	Data acquisition, signal filtering, artifact processing, feature extraction, visualization.
OpenSignals	EMG, EDA, Resp	Biosignal visualization	2012	Yes	Paid (as plugins)	< 5	Data acquisition, Signal visualization, feature extraction
ANSLAB	ECG, EMG, EDA, PPG, ICG, Resp	General Purposes	2004	Yes	Mix Model	< 5	Feature extraction, classification
BioSig Project	EEG, ECoG, ECG, EOG, EMG, Resp	General Purposes	2003	No	Open Source	> 10	Data acquisition, signal filtering, artifact processing, feature extraction, classification, modeling, visualization.
TEAP	EEG, ECG, EDA	Affective computing	2017	No	Open Source	--	Feature extraction, visualization
Augsburg Biosignal toolbox (AuBT)	EDA, EMG, ECG, Resp	Emotion Recognition	2006	Yes	Open Source	< 5	Feature extraction, feature selection, classification.
Physiolab	EMG, ECG, EDA	Fitness Assessment	2016	Yes	Open Source	< 5	Signal filtering, artifact processing, feature extraction, visualization, data interpretation

3.2 Cardiorespiratory radar plots: an informed data visualization technique to support fitness assessment through ECG (R-peak) analysis

All the above-mentioned ECG parameters play an essential role in the CRF assessment. However, the current methods to visualize multivariate physiological data focus on visualizing independent or stacked temporal windows that represent individual parameters. This often results in confusing or overloaded graphs, complicating the assessment by the specialist and limiting the understanding of final users about their cardiorespiratory status. Nevertheless, there are other multivariate temporal visualization techniques designed to facilitate data interpretation.

3.2.1 Radar plotting technique

One method that has recently become popular is the use of radial plotting to visualize multivariate physiological data [140]. StartPlots or RadarPlots are graphical methods for displaying multivariate data in the form of a 2D chart of three or more quantitative variables represented on axes starting from the same point [141]. Each multivariate observation can be seen as a data point in an n-dimensional vector space:

- Arrange $\mathbb{N}$ axes on a circle in $\mathbb{R}^N$ and $3 \leq \mathbb{N} \leq \mathbb{N}_{max}$
- Map coordinate vectors $\mathrm{P} \in \mathbb{R}^N$ from $\mathbb{R}^N \rightarrow \mathbb{R}^2$
- $\mathrm{P} = \{p_1, p_2, \dots, p_N\} \in \mathbb{R}^N$ where each p_i represents a different attribute with a different physical unit.
- Each axis represents one attribute of data. Each data record or data point P is visualized by a line along the data points.
- A line is perceived better than just points on the axes.

In these plots, several axes can be drawn, one for each variable, starting from the middle and equally spaced in a circle. The center represents the minimum value for each variable, and the ends represent the corresponding maximum values.

3.2.2 Cardiorespiratory radar plots and its integration in PhysioLab[3]

Our approach uses the radar plotting technique intending at simplifying fitness assessment through a clear and color-coded representation of the physiological parameters using a multivariate visualization [142]. For the generation of the radar plots, we rely on normative HRV and CRF data to generate three zones or profiles (low-normal-high) by which to categorize users [143]. Each axis of the radar is normalized considering the min and max values of each parameter, therefore avoiding the misinterpretation of

[3] Part of the content of this section was published at: *J. E. Muñoz, S. B. i Bada, E. Rubio, and M. S. Cameira, "Visualization of Multivariate Physiological Data for Cardiorespiratory Fitness Assessment through ECG (R-Peak) Analysis," 37th Int. Conf. IEEE Eng. Med. Biol. Soc. Milan Italy;* and *J. E. Muñoz, E. R. Gouveia, M. S. Cameirão, and S. B. i Badia, "PhysioLab-a multivariate physiological computing toolbox for ECG, EMG and EDA signals: a case of study of cardiorespiratory fitness assessment in the elderly population," Multimed. Tools Appl., pp. 1–26, 2017*.

the area inside of the radar. User's extracted physiological features are plotted in a way that can be directly compared with normative data to facilitate the interpretation of user's cardiorespiratory performance. All axes are divided into three equally sized frames considering the values of the three profiles for each parameter. Before rendering the visualization, a uniform scale is used on every ax for all parameters and for each of the three profile divisions. This approach provides an elegant solution to the "filled in" problem of radar plots, in where the area and shapes of the formed representations change dramatically with data ranges, non-linearity of data, and the order of each parameter in the graph axes [144]. We included the cardiorespiratory radar plots in PhysioLab using a radar plotting menu which allows a previous configuration of the visualization parameters, including age, gender, and type of recording (short or long term). Then, the user can choose 5 out of 7 physiological variables to create the radar plot with the normative data.
Moreover, this normative data is uploaded from an excel datasheet which can be modified by the researcher, thus enabling users to include novel and specific normative data to create the fitness zones. The radar plotting menu is accessed using the option Radar from the Analysis Panel in PhysioLab. Currently, PhysioLab includes only radar plots to assist the data interpretation specifically in the CRF domain, but the concept can be extended to other physiological domains using multiple physiological signals and features. *Figure 2* shows a cardiorespiratory radar plot generated considering HR, SDNN, RMSSD, $VO2_{max}$ and the HRV triangular index.

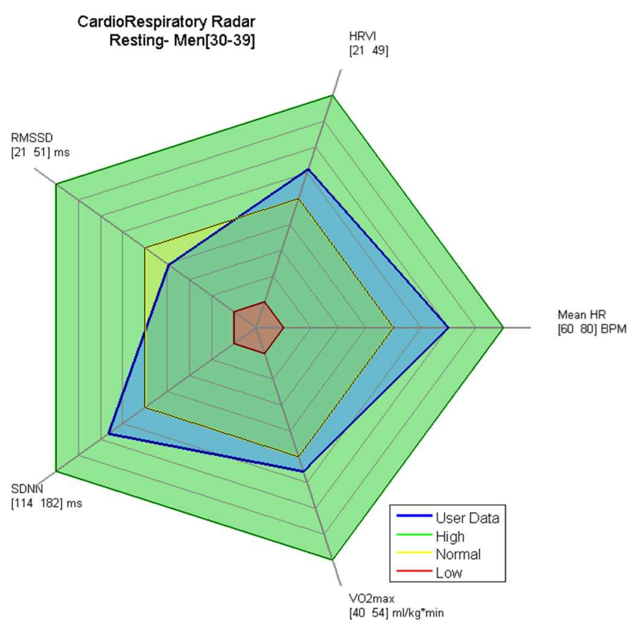

Figure 2. An example cardiorespiratory radar plot generated using MeanHR, VO2max, SDNN, RMSSD and HRV Index parameters.

Performance profiles derived from available normative data are generated and color-coded facilitating the interpretation and comparison of user performance (blue line) with the CRF levels (high-green, average-yellow, low-red). *Figure 2* shows the cardiorespiratory radar for five minutes resting ECG recordings of a 32 years old woman. The final radar plot allows for quick visualization of the CRF state of the user for the activity proposed. In this case, almost all of the parameters are in the high profile of CRF indicating an excellent-superior classification of the user performance. Only the RMSSD parameter reported lower values than the high profile but still within a "safe" average zone (see yellow zone).

3.2.3 Complementing CRF assessment through cardiorespiratory radar plots

To evaluate the usefulness of the cardiorespiratory radar plots to visualize data in the CRF domain, we carried out a study with older adults. The study depicts our very first effort to assess the feasibility of using PhysioLab to complement CRF assessment through physiological signal analysis (ECG in this case) and our radar plotting approach.

Participants
Seventeen healthy older adult participants (14 women, age 64.5 ± 6.4 years, height 1.57 ± 0.67 m, and mass 69.1 ± 12.2 kg) were recruited in a local senior fitness center (see table 3). All participants had no recent injuries in upper/lower limbs, were able to stand up without any support, and had no neurological conditions that prevented the execution and understanding of the experiment. Finally, all participants signed an informed consent form before participation.

Protocol and data collection
Physiological data were collected from the participants during a minimally controlled interactive experience using an Exergame of moderate intensity, in which participants behaved freely playing a Kinect based computer game. The total experience's length was around 30 minutes. ECG signals were recorded during a period of resting (before the interaction) and during the activity. Only the data recorded during the resting state (5 minutes) was used for the CRF radar plots representation. ECG data was recorded using the BioSignal Plux toolkit, a wearable body sensing platform (Plux Wireless Biosignals, Lisbon, Portugal) using a surface-mounted triode dry electrode with standard 2 cm spacing of silver chloride electrodes placed on the V2 pre-cordial derivation. Raw sensor data were acquired with a 1000 Hz sampling rate. The wearable system was connected to a computer through a Bluetooth transmitter placed on the left forearm.

Data analysis
Seven parameters were extracted from the ECG data using PhysioLab: $HR_{resting}$, $HR_{difference}$ (HR during exercise – $HR_{resting}$), HR_{max} (computed using Tanaka's formula, 208-(0.7*Age)), VO_{2max}, SDNN, and RMSSD. Additionally, Energy Expenditure (EE) was directly computed using HR data through the equation of EE ($KJ*min^{-1}$) developed by Keytel et al. [145]. The Metabolic Equivalents (METs), which use as reference the resting metabolic state, was computed assuming one MET equals the resting oxygen uptake (which is approximately 3.5 mL/Kg/min). EE was converted to METs dividing the value by resting energy expenditure [54]. In this way, physical activity can be classified as light (< 3 METs), moderate (3 to 6 METs) and vigorous (> 6 METs) [55]. Finally, a collinearity analysis of the seven parameters

was carried out using Principal Components Analysis (PCA) in order to identify redundancy among extracted features. PCA generates a new set of mutually orthogonal variables (principal components) via making linear combinations of the originals. By plotting multiple principal components in the same space, we can develop a deeper understanding of the driving forces present in the data [33]. Thus, redundant information will appear in the plot with a similar orientation, revealing poor orthogonality.

Cardiorespiratory radar plots

After the PCA analysis, five cardiorespiratory parameters were chosen: $HR_{difference}$, HR_{max}, SDNN, EE, and VO_{2max}. Based on standardized fitness tests (see Senior Fitness Test [146]) data, we grouped the physiological responses according to the above described cardiorespiratory 50+ and 50- fitness profiles and represented them with the cardiorespiratory radar visualization using PhysioLab (*Figure 3*). These cardiorespiratory radar plots provide an alternative graphical characterization of the CRF level of users, through physiological parameters (HR parameters in this case), using as reference normative data of older adults (pentagonal filled color areas).

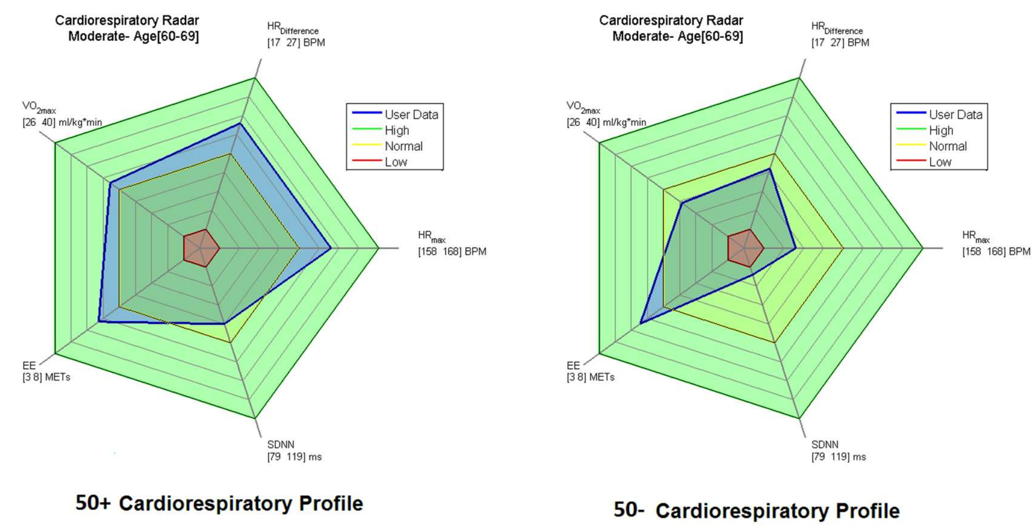

Figure 3. CRF profiles represented by Radar Plots given by PhysioLab for 50+ (left) and 50- (right) performance groups.

The cardiorespiratory radar plots evidence clear differences between groups, and the areas covered by each group are superimposed over age-matched normative data areas. In this example, the cardiorespiratory radar plot approach revealed clear differences between CRF profiles by using five key HR parameters ($HR_{difference}$, HR_{max}, SDNN, EE, and $VO2_{max}$) and normative data for the senior population during resting states. The granularity of our representation to characterize cardiorespiratory profiles allows a more precise and intuitive assessment of aerobic endurance using field data than conventional bar plots. Further, the concept of cardiorespiratory radar plots can also be used to represent multiple performance data of the same user throughout various exercise sessions.

3.3 The Biocybernetic Loop Engine: a software framework for creating physiologically adaptive videogames[4]

The Biocybernetic Loop Engine (BL Engine) is an integrative tool created to design, prototype, iterate and evaluate BLs in videogames and interactive applications made in Unity3D (Unity Technologies, San Francisco, USA). Notably, the BL Engine targets both users with and without expertise in game programming or physiological computing, since it can be fully operated through graphical user interfaces and it uses a simplified method to integrate physiological signals, adaptive rules, and game parameters. The software design requirements included signal acquisition, signal processing, and feature extraction stages as well as a dedicated tool to create heuristic rules for the real-time adaptation [147]. The software can be freely downloaded from https://neurorehabilitation.m-iti.org/tools/en/ble. The software was used for the studies reported in chapter 6 (sections 6.2 and 6.3) where the loop was successfully closed.
The next section summarizes the design and implementation processes as well as our efforts to disseminate the use of this technology.

3.3.1 Software tool positioning

Previous to the software designing process, we identified a set of software tools that have emerged in the last decade to facilitate the creation of BLs and spreading the use of physiological adaptation for multiple purposes. We used *Table 2* as a benchmarking analysis to facilitate the identification of the software features that make the BL Engine unique. Moreover, we identified some features that are still absent in current software tools to create physiologically adaptive videogames, specifically: a) versatility to support multiple body signals; b) integration with game engines; and c) simplicity to create adaptation rules. To tackle the limitations of the existing technologies we have designed the BL Engine.

Table 2. Relevant software tools to create Biocybernetic Loops. BCI: Brain computer interface, VRPN: Virtual Reality Peripheral Network, LSL: Lab Stream Layer. OSC: Open Sound Control

Software Tool	Features and Scope	External Communication	License
OpenViBe	BCI signals. Data acquisition, signal filtering, feature extraction, machine learning.	VRPN, LSL	Open-source (GNU)
Neuromore	Wearable BCI signals. Data acquisition, signal filtering, feature extraction, data visualization.	OSC	Paid
FlyLoop (Java Framework)	BCI, Eye Tracker and any streamed input from physiological sensors. Data acquisition, signal filtering,	Java	Open-source (GNU)

[4] Part of the content of this section was published at: *J.E. Muñoz, E. Rubio, M. Cameirao, and S. Bermúdez, "The Biocybernetic Loop Engine: an Integrated Tool for Creating Physiologically Adaptive Videogames," in 4th International Conference in Physiological Computing Systems, Madrid, España, 2017.*

	probabilistic learners, sensor fusion.		
NeuroPype	BCI, Motion Capture and Eye Tracking. Data acquisition, signal processing, artifact removal, data visualization.	LSL, Phyton	Paid
MakeWear	Heart rate and physical movement. Data acquisition, communication with physical actuators (e.g. sound, lights, vibration.	Blockly (JavaScript)	Open-source (GNU)
Biocybernetic Loop Engine	Heart rate, affective data (facial expression), wearable BCI (Reh@Net). Data acquisition, signal filtering (cardiac), feature extraction, communication with games developed in Unity3D.	C# (Unity3D)	Freely Available

3.3.2 Software design

Design Requirements

The BL engine software was designed to be used by people both with and without specific training in physiological computing and programming skills. We identified a list of implementation requirements that guided the design of the BL Engine in signal acquisition, signal processing, and feature extraction, and adaptation domains, as well as its integration with other software systems.

Signal acquisition, signal processing, and feature extraction: one of the most significant limitations when using physiological signals in interactive projects is the connectivity with multiple devices. The lack of standardization of components, different communication protocols, and measurements offer a highly variable scenario [94]. Thus, the BL engine should facilitate and streamline the signal acquisition process. Further, the real-time signal processing of the acquired signals is an engineering challenge [85], and thus, the inclusion of common filters to process signals is imperative. Finally, although the features commonly extracted from physiological signals to carry out psychophysiological inferences are relatively well-defined [67], their use for biocybernetic adaptation is still not well understood. Hence, the extraction of meaningful physiological parameters from sensor signals is necessary as they are the primary input of the BLs.

Adaptation: the second set of requirements relates to the design of the adaptive rules, which contain the intelligence of the BL system. Mostly, these rules encompass the decision-making process underlying physiological adaptation. Although simple Boolean rules based on if/then rules have been successfully used in past investigations [148], more advanced techniques based on proportional-integral-derivative control [29] and machine learning approaches [150] have also shown encouraging results. Despite those advances, the implementation and iteration of adaptive rules in BLs require extensive reprogramming processes in order to create playable prototypes [29]. Consequently, our BL engine should embrace an agile methodology that facilitates the generation of adaptive rules and enables a fast iteration on them.

Integration: finally, full integration with third-party software systems, such as videogames, is required. Even though great game engines are freely available (e.g. Unity3D, Unreal Engine), the integration of physiological computing technologies in those systems is not a simple task due to the lack of standardized and functional signal processing toolboxes [91]. Only a few examples enable the integration of physiological sensors with the Unity3D game engine such as the PhysSigTK [151], RehabNet CP [152], and PhysioVR framework [153]. However, BLs require not only a simple integration of sensors but also a bi-directional communication between the extracted physiological parameters and the videogame variables in real-time.

Software Design Process
The BL Engine aims to be an extensive tool for the creation of BLs in multiple dimensions such as cardiac, muscular, emotional or motor domains. We developed a cardiac module and tested its functionality by implementing a BL in gaming applications. More acquisitions panels have been integrated to extend the BL Engine as a multimodal software tool. We used multiple techniques from software engineering for the development - process workflow understanding, activities, and system dynamics visualization relying on flow and UML diagrams of the system, and low fidelity prototyping through digital interactive wireframes - before its implementation.

3.3.3 Software Implementation

The BL Engine allows users a simple designing and prototyping processes of physiological adaptations in videogames by following the complete processing pipeline from physiological data collection and analysis to the final translation in videogames (*Figure 4. The BL Engine system architecture illustrating the main components of the framework*).

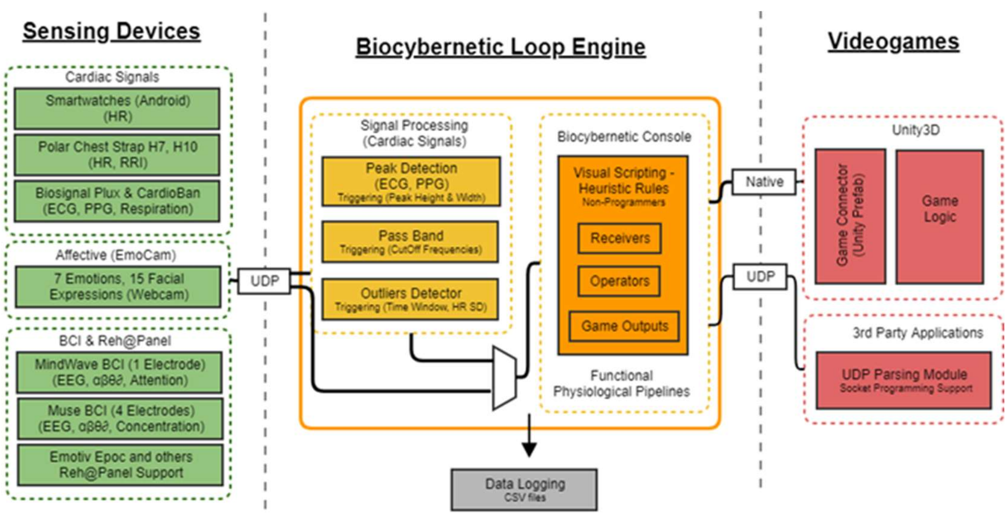

Figure 4. The BL Engine system architecture illustrating the main components of the framework.

Signal Acquisition Panels

The BL Engine uses external clients to provide access to the sensors' services and make them available for further processing. The clients are developed in different programming languages such as C++, C#, and Android, and they stream data from sensors through User Datagram Protocol (UDP) following the Reh@Net communication protocol [152]. The main menu was designed to facilitate the navigation between the different acquisition panels named Cardiac, Emocam, and RehaPanel, as well as provide options to manually configure the UDP parameters to receive the physiological data and communicate with the games.

Cardiac Signals (Figure 5): the BL engine supports the acquisition of cardiac-related signals such as electrocardiography (ECG), heart rate (HR), photoplethysmography (PPG), and heart rate variability (HRV) from a basic range of wearable devices including:

- Android Smartwatches, which provide computed HR data.
- Polar Chest Straps (H7, H10), which provide computed HR and RR intervals (RRI) data.
- Biosignal Plux Kit and CardioBan ECG-Respiration-Acceleration chest strap band, which include sensors to measure ECG, PPG and respiration data.

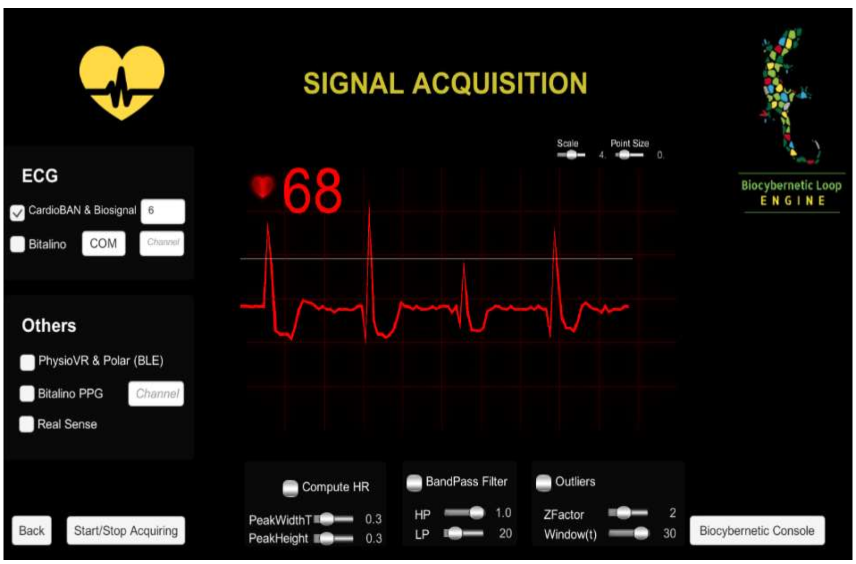

Figure 5. Screenshot of the Signal Acquisition Panel in the BL Engine. The image shows an ECG signal from the CardioBan chest strap (PLUX, Lisbon, Portugal) with the computed HR.

This acquisition panel integrates a signal visualization module to aid real-time data analysis and feature extraction from raw data (such as ECG and PPG). Moreover, we also included algorithms for HR computation based on an adaptive peak-detection technique. Parameters for peak detection can be tuned to improve HR extraction (e.g., width and height of the peaks). An adjustable band-pass filter can also be used to improve signal quality and HR detection. Finally, an outlier detection algorithm was implemented to clean outliers from HR data mainly produced by movement artifacts [147].

Affective parameters from facial expressions (Emocam Panel, Figure 6): by using the Affectiva SDK [154] tool for real-time facial expression recognition, we created the *Emocam*[5] acquisition panel. This panel allows capturing data of 7 different emotions and 15 facial expression metrics and 2 alternative metrics as follows: i) emotions: joy, anger, disgust, surprise, fear, sadness, contempt; ii) facial expressions: attention, brow furrow, brow raise, chin raise, eye closure, inner brow raise, lip corner, lip press, lip pucker, lip suck, mouth open, nose wrinkle, smile, smirk, upper lip raise; and iii) alternative metrics: engagement and valence. This panel uses simple webcams to compute the features, which are streamed using the Reh@Net protocol to create the adaptation rules. Furthermore, it allows saving the features extracted for a post-session analysis.

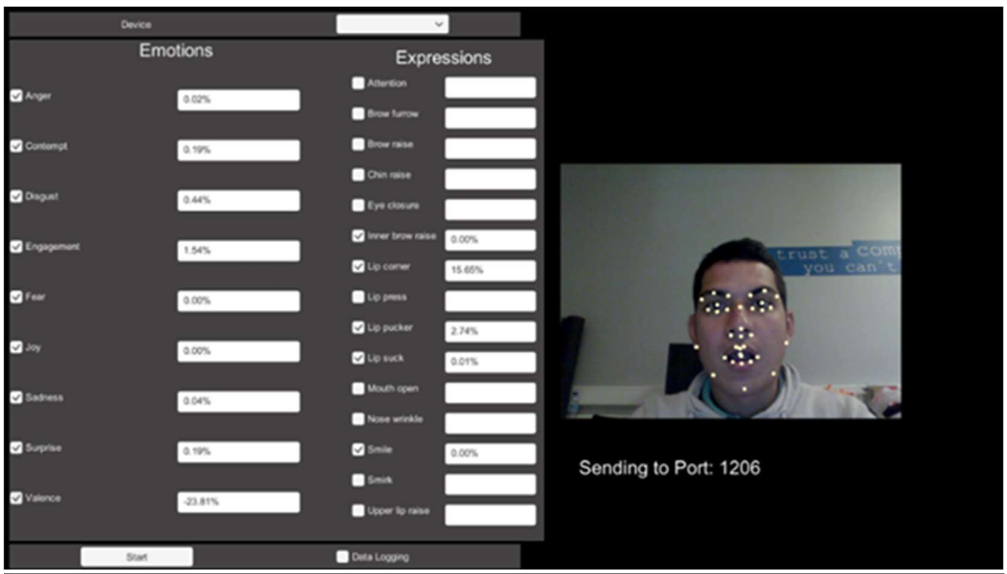

Figure 6. Screenshot of the EmoCam panel which uses the Affectiva SDK to translate facial expressions in affective information.

Wearable Brain-Computer Interfaces and the Reh@Panel: three wearable BCI systems are supported in the BL Engine:

- Mindwave BCI: an external client[6] developed in C# stream data related with the high and low power levels of α, β, θ, and ∂ oscillatory rhythms as well as the computed meditation and attention levels.
- Emotiv Epoc: by using the Reh@Panel software [152], the raw electroencephalography (EEG) data from sixteen electrodes as well as the expressive (e.g., blinking, smiling) and affective (e.g., frustration, boredom) features of this wearable sensor can be accessed.

[5]EmoCam was developed by Diogo Freitas as part of his undergraduate thesis project entitled: *EmoCam: capturing emotions using non-invasive Technologies, Universidade da Madeira (2017).*
[6] https://neurorehabilitation.m-iti.org/tools/en/neuroskydemo

- Muse BCI: by using the Muse Lab standalone application[7], raw EEG data from four frontal-lobe electrodes can be accessed as well as the power of α, β, θ, and ∂ oscillatory rhythms of each score.

Finally, the BL Engine also provides access to the Reh@Panel software which supports other physiological devices such as eye trackers and DIY kits (e.g., Bitalino, OpenBCI).

Biocybernetic Console: as a tool to create adaptive rules, the biocybernetic console utilizes the output from any acquisition panel (e.g., HR, engagement, EEG β power) to influence the videogame functioning (*Figure 7*). The BL console uses a visual scripting module, which comprises the use of pre-programmed boxes that can be graphically connected to create adaptive rules through functional physiological pipelines (FPP). The blocks can be dragged-and-dropped from the right-side canvas to the left workspace, and the inputs and outputs of the boxes can be connected by drawing connection lines. Additionally, the workspace size can be modified allowing the creation of multiple FPPs that can run in parallel using inputs from different physiological sensors. The blocks fall into three different categories:

- Receivers: blocks that receive and/or simulate data. Here, we can receive data directly from any of the signal acquisition panels or data coming from any external application supporting socket programming through the UDP Reh@Net and OSC (Open Sound Control) protocols.
- Operators: blocks that make comparisons, mathematical and logical operations, and variables' assignments. Blocks for adding constants and visualizing results are also implemented.
- Game outputs: blocks for modifying game variables in real-time. Game variables are exposed to the BL Engine using the Unity3D Game Connector module or through UDP for third-party applications.

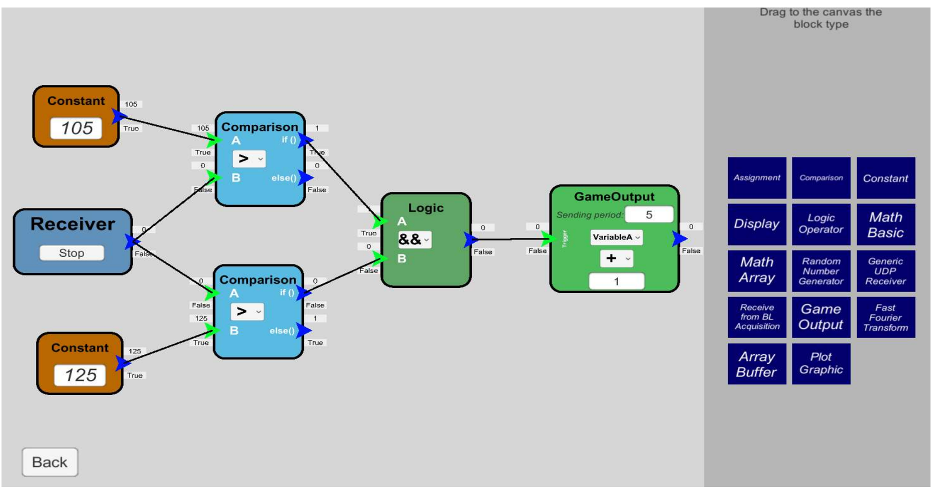

Figure 7. A possible Functional Physiological Pipeline (FPP) created in the Biocybernetic Console of the BL Engine.

[7] http://developer.choosemuse.com/tools/mac-tools/muselab

After the rule creation process, users can test its behavior in real-time and iterate with multiple adaptive rules during run-time. Data from both the BL Engine and the videogame can be recorded for post-processing using a CSV data writer script.

Game Connector

To enable the connectivity between the BL Engine and the videogames, we provide the game connector module, which is wrapped into a prefabricated package (prefab) that can be integrated into any videogame developed in Unity 3D. The Unity prefab package contains the scripts needed for bidirectional communication with the BL Engine. The connector receives the physiological data via UDP communication, makes specific videogame variables available to the Biocybernetic Console for the creation of the adaptation rules, and updates them in real-time accordingly. Any third party application supporting socket programming (such as Unreal Engine and others) can also receive data from the biocybernetic console via a UDP parsing module.

3.3.4 Open Source Game Library for Experimentation

With the ultimate goal to promote the use of the BL engine by researchers, game developers, and technology enthusiasts, we created an open source library of game projects developed in Unity3D. A total of eight open-source game projects from the Unity asset store were adapted to be used with the BL Engine (*Figure 8*).

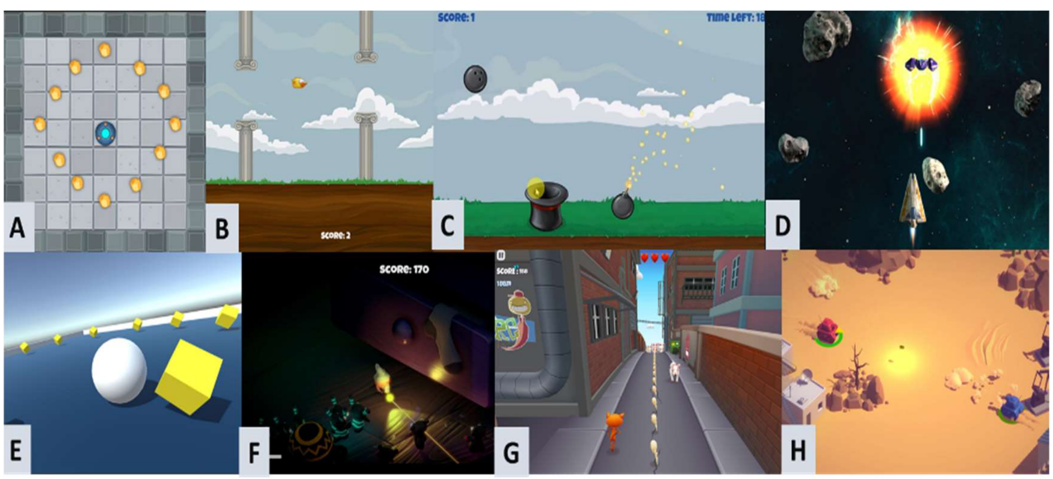

Figure 8. Screenshots of the open source game project available and customized to be used with the BL Engine. A. 2D UFO, B. Flappy birds, C. Hat tricks, D. Space shooter, E. Roll a ball, F. Survival shooter, G. Trash dash, H. Tanks.

One of the most critical steps in integrating the BL Engine with any videogame is the definition of the game variables that will be driven by the physiologically adaptive rules. In all the games at the library, we previously identified the game variables that can be potentially used to create the adaptive rules (*Table 3*).

Table 3. Open-source library game projects available to integrate with the BL Engine. All games were developed for Unity Technologies and modified to be easily used with the BL Engine.

Game Project	Description	Game Variables
A. 2D UFO	2D object collection game	Player speed
B. Flappy Birds	Side-scrolled 2D game	Jump force, column pool size, spawning rate, column min-max values.
C. Hat Tricks	2D Object-catch game	Hat movement speed, Ball falling speed
D. Space Shooter	Top-down arcade shooter	Ship: speed, tilt, fire rate. Weapon: fire rate, delay. Asteroids: speed. Enemies: speed, fire rate.
E. Roll a ball	3D objects collection game	Player speed
F. Survival Shooter	3D, top-down shooter	Player: speed, health. Enemies spawning time.
G. Trash Dash	Endless runner	Lane change speed, min-max speed.
H. Tanks	Multiplayer tank combat	Tank speeds, fire rate.

Besides, we designed a hands-on workshop to divulge the use of the BL Engine via learning how to integrate it with the games described above. The first one-day workshop was carried out in the International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2018), and attendees were able to learn the theoretical basis of BLs, case scenarios and carry out the hands-on with the games presented. The game projects, BL Engine, and instructions on how to adapt games and videos of the presentations can be found at the workshop website[8].

3.4 Conclusion and Discussion

The here reported development of the software tools constitutes our early efforts in trying to aid the integration of physiological computing and gaming approaches. Despite the existence of several software tools available for aiding the research on physiological computing, we have positioned PhysioLab with the CRF radar plots and the BL Engine in the broad spectrum of freely available tools. In this chapter we introduced the tools that were transversally used along with this thesis, allowing the iterative software design and implementation process to take place before, during and after the field studies to bring usable and user-friendly software tools to the community.

Firstly, PhysioLab is a multivariate signal toolbox created to simplify physiological signal processing, especially for out-of-the-lab fitness experiments. The toolbox is intended to assist both researchers and non-experts in the arduous task of processing physiological signals, allowing cross-comparisons between each signal, an automatic feature extraction with manual adjustments and providing a novel visualization. The software provides a wide variety of signal processing methods and artifact removal filters for EMG, ECG, and EDA signals and it is entirely operated using a

[8] https://sites.google.com/view/physio2games

graphical user interface. Secondly, PhysioLab contains a novel tool to visualize multiple physiological parameters in specialized fitness domains using radar plots, providing contextual normative data to facilitate data interpretation. Specifically, we believe that the inclusion of radar plots in the CRF domain allows: a) an easy comparison between individuals with average-profiles of the population, b) multiple comparisons between subject's exercise performances at different moments, and c) versatility to include multiple HR-based metrics with normative data to assess users' performance.

Lastly, the BL Engine framework provides a comprehensible and streamlined method to add physiological intelligence to games and interactive applications in both non-immersive and immersive scenarios. A better understanding of using biocybernetic adaptation principles can be achieved by means of using the BL Engine which includes the tools needed for the simplified acquisition, analysis, and transition model. The BL Engine utilizes a fully functional and modular user interface and integrates a visual scripting module, which facilitates programming the adaptation rules. Moreover, it provides tools for a simplistic integration of any videogame developed in Unity3D.

The here documented tools are part of a carefully and highly iterative process carried out to facilitate the study of the physiological phenomena during the interaction with Exergames. Moreover, its use can be extended in many different interactive applications that cover both real-time and post-processing analysis of physiological signals.

4 Exergame Design Through Human-Centered Methods

In this chapter[9], we summarize our efforts towards designing contextually-rich Exergames for functional fitness training in the Portuguese older population. We used a set of techniques from a human-centered design approach to investigate about users' preferences and motivators to play Exergames at the senior gym. After a very detailed process that includes the feedback from games for health experts and sports science professionals, we came up with a set of fully customizable, enjoyable and contextualized Exergames.

This chapter describes our effort to introduce a structured and systematic methodology for the design of Exergames targeted at older adults. We designed and developed a set of Exergames, which combine standardized fitness training programs and a contextually rich user modeling process to overcome current limitations in the use of Exergames by older adults. For that, we introduce a design framework that addresses critical aspects:

- Human-centered approaches in different stages of the game design process.
- Emphasis on fun experiences through playful interaction and gamification elements (story, aesthetics, mechanics, and technology).
- Integration of health professionals in the process to identify health-related standards to be incorporated in the Exergames.
- Rapid prototyping and fast iteration with end-users.

The next section presents the whole design process from the definition of the health requirements to the final polishing stage of the proposed Exergames. Our experimental scenario is a senior gymnasium frequently used by active adults to exercise, socialize with their peers, and participate in several cultural activities. Our goal goes beyond researching in exercise motivators and training programs adoption. We aim at inquiring into methodologies to design enjoyable and scientifically valid Exergames to promote exercise in older adults by adopting human-centered design processes.

4.1 Exergames design and development

We started the process by designing a set of Exergames from the examination of health requirements. A complete process diagram can be seen in *Figure 9*, which depicts all the steps from the conceptualization until the polishing stage.

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[9] Part of the content of this section was published at: *Gonçalves, A., Muñoz, J., Gouveia, É., Cameirão, M., & Bermúdez i Badia, S. "Portuguese Tradition Inspired Exergames for Older People" in 6th International Conference on Sport Sciences Research and technology Support, Funchal Portugal (2017)* and *Muñoz, J., Gonçalves, A., Gouveia, É., Cameirão, M., & Bermúdez i Badia, S. "Lessons learned from gamifying functional fitness training through human-centered design methods in Portuguese older adults" in Games for Health Journal (2018 – Accepted).*

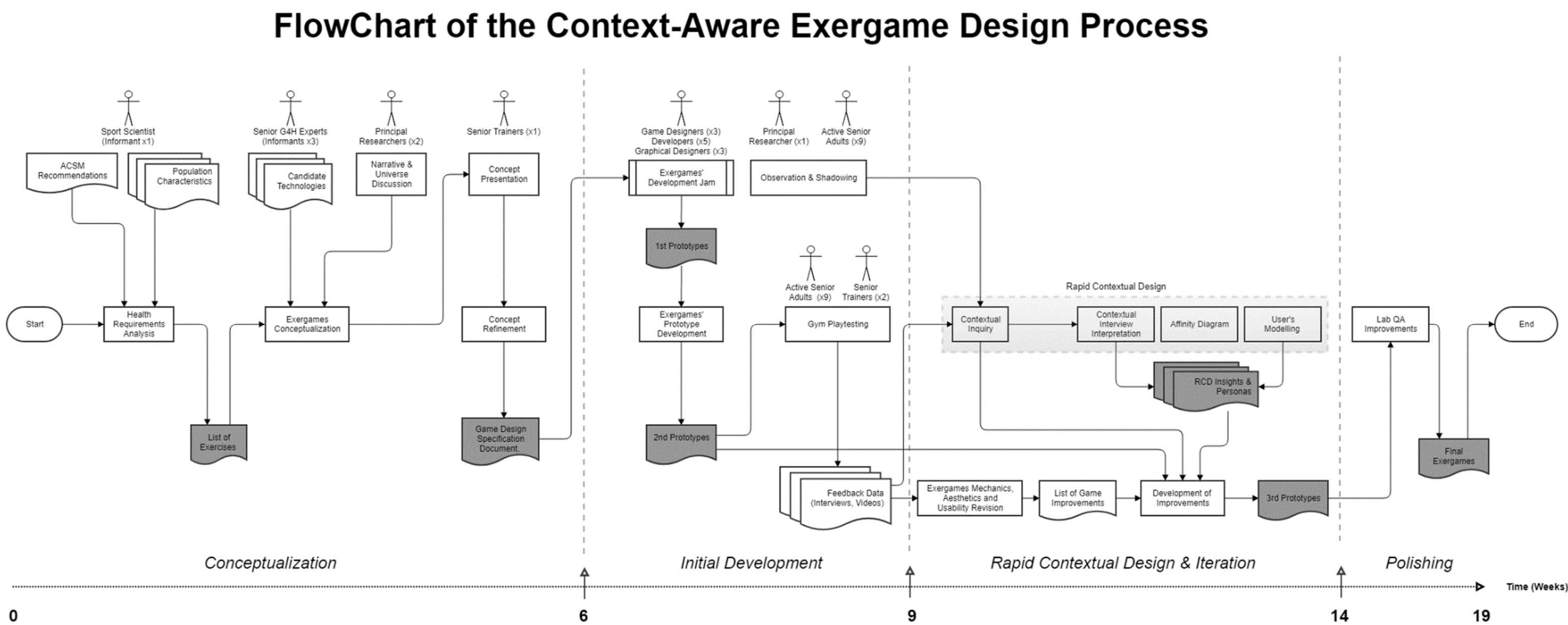


Figure 9. The flowchart diagram of the design process describing people involved, inputs, deliverables and design stages. The duration of the process was 19 weeks divided in four main stages: conceptualization, initial development, rapid contextual design and iteration and polishing.

4.1.1 Exergames conceptualization

Requirements and input from experts

Two different sources of information were used for the health requirements analysis: a) population characteristics (health screening) and b) assessment of functional fitness status [155]. We identified the relevant components to be trained and measured via Exergaming to be: motor ability (balance, agility, and flexibility), aerobic endurance and muscular strength (lower and upper limbs, and trunk). Additionally, we identified three level of training profiles: low, moderate and high functioning. These profiles will allow balancing the intensity of training to user fitness levels, also called the effectiveness loop in the dual flow model [156]. For the videogame design process, we included sport science professionals with experience in older adult's fitness training and assessment. They were encouraged to illustrate several exercises, movements and/or activities that users need to perform to training each of the domains in the different training profiles. Appendix A contains a list of exercises suggested by the sports professionals. The biggest challenge in the game design process was in the ideation of an Exergame universe that would embrace the specified health requirements. How can we design fully-enjoyable Exergames starting from pre-defined fitness/exercise recommendations avoiding the chocolate-covered broccoli effect [157]?

Technology Selection

First, we gathered with three senior researchers of games for health to define an initial set of candidate technologies that would be adequate for a training program based on Exergaming. Motion tracking and physiological computing technologies were considered for the design of an integrated solution that could be used in both controlled (e.g., laboratory) and non-controlled (e.g., senior gymnasiums) environments. Finally, the Kinect V2 motion tracker system was chosen because of its non-invasive method to record kinematic data as well as its low cost. Besides, the Kinect V2 sensor allows an accurate (1 cm to 5 cm [158]) tracking of 25 joints distributed along the whole body for standing and sitting postures [159]. For all the Exergames, we decided to use a floor-projection setup to facilitate the matching between game mechanics and physical activity. One of the advantages of using floor-projection setups for videogame interaction is the possibility to use large physical surfaces avoiding spatial constraints [160]. The setup includes a white PVC surface (2.5m m x 3.0 m), the Kinect V2 sensor located ~4m in front of the users and a PC. To facilitate the interaction, we also explored the use of spatial augmented reality which allows the augmentation of real-world objects and spaces using simple projections instead of special displays [161]. With this technology, users can physically interact with the objects placed in virtual environments and projected on the floor in real scale.

Game ideation

For the Exergame's ideation stage, we used brainstorming [162]. We focused on the creation of multiple videogame stories enclosed in imagined virtual scenarios in which users' playful interactions would be masked exercises. These scenarios would define a narrative and a universe for the

Exergames. After approximately ten short (20 min) brainstorming sessions involving game designers and sports professionals, we came out with five categories of activities, each with multiple possible scenarios as follows:

- Fantasy: space exploration, medieval live, maritime activities, and aviation.
- Sports: Olympic Games, traditional Portuguese games, and martial arts.
- Professional manual labor: agriculture, food preparation, animal care, mineral exploration, gardening, hospital activities, automotive mechanic, child-care, and construction work.
- World traveling: continental or national tourism.
- Creative oriented activities: painting, sculpting, dancing and fashion design.

These ideas were combined with the pre-defined exercises for physical training, and we decided to choose the world-traveling category to develop a virtual tour in Portugal. We based our choice on the hypothesis that via culture-specific elements, users with low-levels of technology literacy would feel more identified and engaged with the Exergame experiences. Initial ideas involved developing Exergames to perform several Portuguese activities around the most popular touristic places in the country. The idea was then presented and discussed with a fitness trainer in a local senior gymnasium and the concept was refined identifying motivating places and activities that could engage the senior audience (see *Concept Presentation* and *Concept Refinement* in *Figure 9*). A game design and specification document were produced detailing initial ideas for possible exercises taking place in the imagined virtual universe (as recommended by game design frameworks [163], [164])**.** Once the core of the story component was established, we engaged in the development of the game mechanics in a game jam [165].

4.1.2 Exergames development Jam

After the conceptualization, we used a rapid iterative prototyping approach [162], which was implemented in a local game jam. The jam was carried out in a research laboratory facility and lasted about 40 hours along five consecutive days. The very first activity carried out was a visit to the local senior gymnasium where participants had the opportunity to observe regular exercise sessions with a group of around 30 senior adults. Three videogame designers, three graphical artists, two psychologists, two sport science professionals, five programmers and three games for health experts participated actively. Teams were established trying to cover different fitness domains following the health requirements described before. We emphasized and prioritized the importance to make Exergames appealing, meaningful (regarding health and social benefits), and playable for older people with different preferences [166]. Since this population is very heterogeneous, the development of a generic and poorly personalized experience will end up in a minimal solution for exercise promotion [11].

Three different presentations of playable demos took place during the Exergame jam for evaluation of the prototypes. Two health professionals from a senior gymnasium and three games for health experts evaluated the videogames in different stages. At the end of the development jam, the first version of the prototype Exergames was completed in: a) 60% of game mechanics, b) 80% game story, and c) 20% of game aesthetics. At this stage, we had a set of experiences covering four different places in Portugal that addressed all fitness domains. Prototypes were further developed (see *Exergame's prototype development* in *Figure 9*) and iterated until they were robust enough to carry out a field test in a local senior gymnasium in Madeira, Portugal.

4.1.3 An Exergaming Experience through Portuguese Traditions

At the end of the one-week jam, our vision to create a virtual tour in Portugal was materialized with a set of Exergames covering several touristic activities in different places (*Table 4*).

Table 4. Description of each individual Exergame, Portuguese tradition, goal, fitness domains addressed and related movements.

Exergame (Portuguese Region) description	**Goal and Score**	**Fitness Domain and Movements**
Grape Stomping (Douro Region): winemaking through crushing grapes barefoot to release the juice.	Goal: Stomp grapes to produce wine by stepping on virtual grapes placed into open tanks. Score: liters of wine produced.	Cardiorespiratory Training: flexion-extension arm movements are needed to drag the grapes into the tanks. Then, the stomping process starts, requiring users to raise the knees repeatedly. After filling up one tank, users can move to the others to continue the exercise.
Rabelos (Porto City): wine transportation in barrels through cargo boats navigating in the Douro river.	Goal: Transport barrels of wine along the Douro river by rowing in a boat avoiding rocks and collecting more barrels in the riverbanks. Score: quantity of barrels collected.	Upper limb muscular strength: perform circular arm movements simulating rowing gestures to move the boat forward. For lateral displacements of the boat, standing users can use either lateral movements or trunk leaning; or they can be seated and use trunk leaning only. To navigate the rapids, users must avoid rocks by rapid lateral movements. To pick up the barrels, users must turn the trunk to the dock and make an extension-flexion movement of the elbow.
Exerfado (Libson City): Fado music playing by a melodic guitar soundtrack.	Goal: Catch the correct notes by selecting of the frets in a virtual guitar (GuitarHero-like game). Score: number of successfully collected musical notes.	Lower limb, Flexibility: players collect notes by performing rapid lateral movements to select the correct guitar's fret. Players should move their entire body to collect the musical notes since the paddle reflects the movement of the hip. Once empty, the music score can be refilled using a "turn the page" or swipe gesture with the left hand extended.
Toboggan Ride (Madeira Island): a downhill journey in a sledge sliding car.	Goal: Control the direction and acceleration of the car to collect items placed on the street Score: number of successfully collected banana bunches.	Balance, Trunk muscular strength: The sledge direction is controlled via trunk lateral flexions while the acceleration is controlled through trunk flexion-hyperextension movements. Flexion movements are used to increase the acceleration of the vehicle while hyperextensions are used to deaccelerate it.

4.2 Applying human-centered design methods for inquiring about Exergaming preferences

4.2.1 Hands-on in the rapid contextual design

After the game jam, the next efforts were centered in the testing of the second version of the prototypes with end-users and the collection of structured feedback. Following the focused RCD process, we designed three different surveys: a demographics form, a videogame experience questionnaire, and a final survey from which we collected feedback related to the Exergaming experience.

Demographics
Participants for this study were selected from the older adults' population exercising (at least two hours per week) in the senior gymnasium. Participants were addressed by the gym trainers to collaborate in a structured interview which included interaction with a gaming system under development that would potentially be used to complement their exercise routines. Volunteers included nine (9) older adults (8 females, M=62.3, SD=6.2) who signed an informed consent before participation.

Contextual Inquiry
Since attitudes, behaviors and personal opinions are generally challenging to capture, observation and shadowing of users [167] during the work-out time was performed on different days during the two weeks preceding the data collection process. We conducted frequent informal conversations with end-users to aid the identification of relevant contextual information. Interviews took place in the exercise room of the gymnasium, and the surveys were individually delivered.

The videogame experience questionnaire (Appendix C) was used to investigate two main topics:

- Patterns of digital gameplay: frequency, intensity, past history, social aspects and perceived skillfulness of gameplay.
- Motivators to play: how started playing, favorite games and videogames, attractive elements for videogames, interest to start/continue playing.

The interviews were semi-structured questionnaires with one interviewer and one note-taker present. We asked a pre-determined set of questions and tailored each inquiry with follow-up questions based on each interviewee's answers. This strategy was made to encourage interviewees to expand on their initial comments.

Contextual interview interpretation and user's Personas
Following the focused RCD methodology, we conducted:
Contextual interview interpretation: we analyzed the exercise routines of the older adults in the gymnasium, their socialization, and relationship with colleagues and fitness instructors. We were focused on identifying intrinsic motivators, main barriers and possible facilitators for exergaming for our local population in their gymnasium.

Work modeling: we focused on the development of multiple sequence models of daily exercise practice in the gymnasium, which represent the ordered steps in which a senior performs the prescribed activities. Subsequently, we designed possible scenarios of interaction with the Exergames inside the gymnasium and represented them as sequence models of activities. This helped us to envision future user experience issues and contrast them with the information collected from the real interaction using the digital prototypes.

Affinity diagram: during the observation and shadowing processes, detailed field notes were taken, coded and subsequently merged with the notes from the contextual inquiry and Exergaming experience. Since we were interested in viewing the opportunities to integrate Exergaming practices in the senior gymnasium, an affinity diagram was used as a starting point for constructing design considerations. The diagram revealed information regarding the user's habits and behaviors during exercise practice in the gymnasium as well as connections between technological elements and the user's perception of videogames. The affinity diagram was used to a) categorize older adults, considering their opinions and experiences with technology, and b) compile a list of insights and design ideas to modify the Exergames considering the feedback gathered from the users and instructors.

User Personas: user's archetypes for the active senior population were modeled according to the treated information. We focused on their willingness to integrate videogames into their lives. We identified two main types of information to create our user's Personas:

- Personal habits and physical activity practice: information related to the activities during the leisure time, ways to exercise, preferences regarding activities of daily life, and frustrations.
- Technology literacy and game experience: information regarding past experiences with gaming devices such as videogame consoles, PCs, and mobile devices were considered to create a technological curriculum for the seniors. We focused on the motivators to play Exergames such as social elements, health issues, and curiosity.

The models for the user's Personas contained the following information:

- Basic information: a picture of the processed archetype, a small quote reflecting a personal opinion about videogames, hobbies, and preferred activities (such as traveling, exercising, and having fun with children).
- Personal information: a short-biography describing some characteristics of the user's personality such as preferences and habits, together with the physical activity agenda and representative goals and frustrations.
- Technology literacy and willingness to the games: technology literacy is primarily expressed regarding past experiences with computers, mobile phones and tablets, and videogame consoles. Six bar scores denote specific motivations to play Exergames - fun and pleasure,

escape from daily routine, social interaction, physical health, mental health, and curiosity in new experiences.

Two realistic and one idealistic user Personas were modeled. The realistic models are a Skeptic and a Curious archetype, referring to the senior's willingness to use videogames in her daily routines. The skeptic persona (*Figure 10*) is characterized by having distrust over the possible health and social benefits of using videogames. This fact is strongly based on the limited past experiences older adults had with gaming technologies that reflects a simplistic vision of playing videogames: a waste of time. More than a half of the interviewed users were identified as Skeptic users.

Figure 10. Image representing the model from the realistic senior Skeptic Persona.

The Curious Persona (*Figure 11*) is not indifferent to the incorporation of technology into her daily life activities. She had some previous experiences with videogames, and it had a positive impact on the perception of how useful videogames can be regarding social interaction and fun. Curious users are more prone to accept the use of Exergames for exercising.

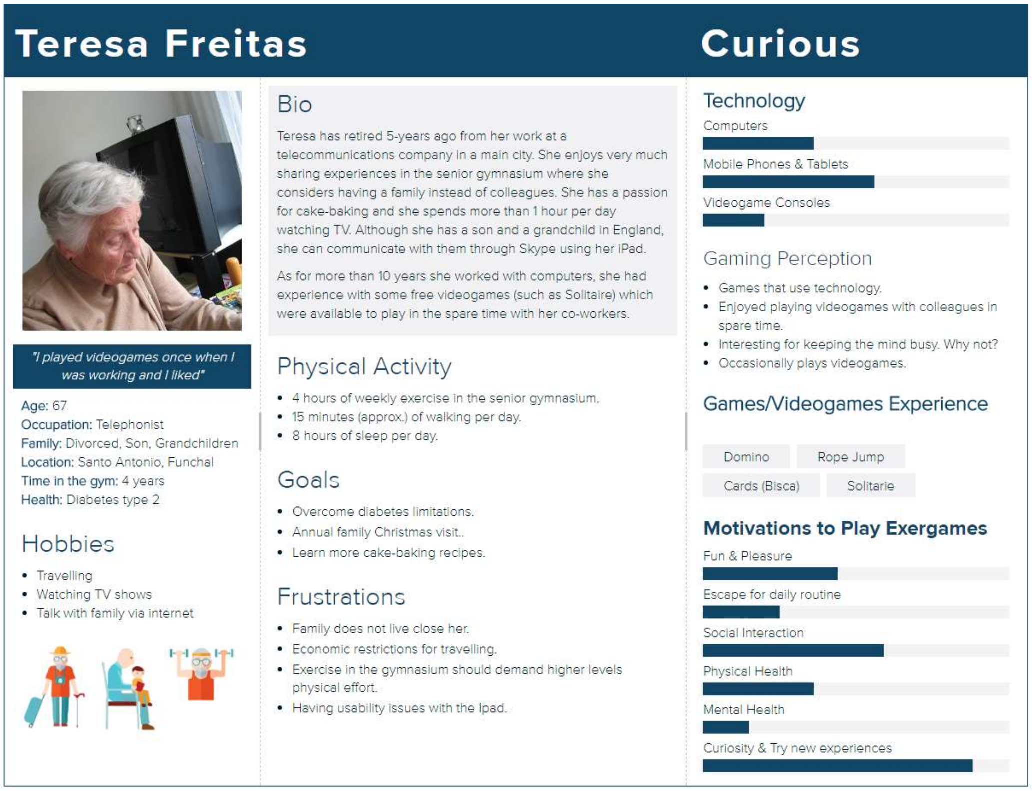


Figure 11. Image representing the model from the realistic senior Curious Persona.

Finally, the ideal user: The Enthusiastic (*Figure 12*). Although in this research we did not find active senior gamers, we wanted to model the ideal user to understand the conditions for the long-term adoption of Exergaming. The Enthusiastic archetype has a medium-high ability to interact with either computer, mobile devices or videogame consoles. This user uses videogames in her daily life routines strongly believing in its health and social benefits.

The consolidated models and the revealed affinities were evocative representations of the interviewed older adults. These models cover an amalgam of elements such as fitness habits and characterization, social behaviors in the gymnasium, personal perception about the use of technology for working out and characteristics of senior needs regarding engagement, and motivation to make exercise routines.

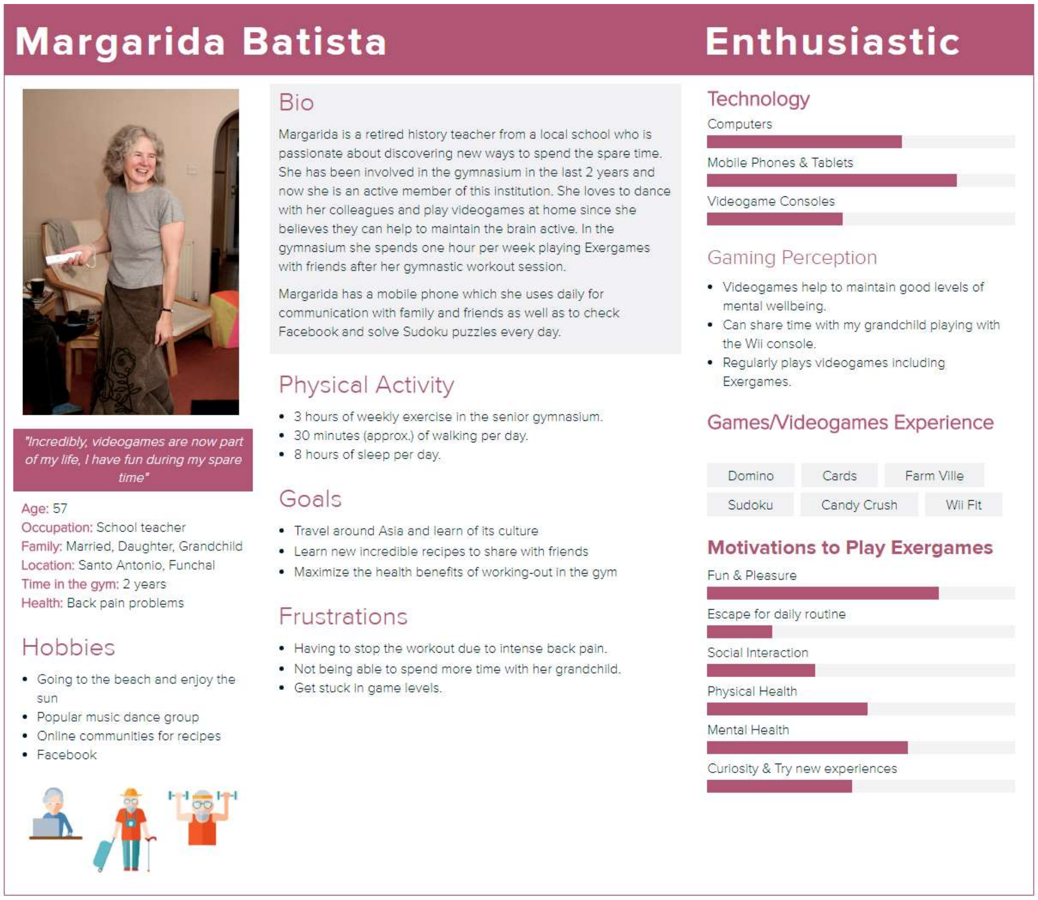


Figure 12. Image representing the model from the idealistic senior Enthusiastic Persona.

4.3 Iterations and feedback

4.3.1 Playtesting with the target population

Having the second version of the prototypes of the Exergames, we decided to carry out a first playtest with the target population at the senior gymnasium with the same users that participated in the contextual inquiry (see Gym Playtesting in *Figure 9*, Appendix C). The interaction with each Exergame took about 5 minutes and then users were asked to enumerate: a) three videogame elements they liked, b) three videogame elements they did not like, and c) three things they would like to add/remove from each Exergame. Finally, we asked their opinion on how to integrate the Exergames in the gymnasium. Videos from the experience were recorded to be analyzed afterward (see *Feedback Data* in *Figure 9*). We also carried out informal interviews with two exercise instructors from the gymnasium to understand their needs and reactions to the Exergames. They supported the Exergame's mechanics, the story theme, and provided specific requirements such as:

- Including strategies to gradually teach movements one at the time.
- Increasing the challenge to guarantee more workout time.

- Allowing broader customization of the videogame parameters to facilitate difficulty adjustment and the inclusion of seniors with limited movement.

After gathering the feedback from the users and instructors, we carried out multiple development iterations on the prototypes aiming at improving the mechanics and aesthetics as well as the usability of the system (*see Exergames Mechanics, Aesthetics and Usability Revision* in *Figure 9*). A list of improvements was merged with the user's Personas models and the insights of the RCD process to generate the 3rd generation of the Exergames. Final polishing tasks were developed in the research laboratory before releasing the final version of the Exergames after 19 weeks.

Merging the information from both RCD and Exergaming feedback, we observed:

- Social aspect: older adults enjoy playing mainly for two reasons: they like to win competitions and they find here an opportunity to socialize (skills and experiences). Multiplayer playability is a crucial factor to improve technology adoption.
- In-time feedback: for both skeptic and curious profiles, the lack of past experiences with gaming technologies obstructs a fluid interaction in different stages. High quality and frequent feedback in the videogame to facilitate the understanding of what to do, how to do it and when, is imperative.
- Customization of movements: options for personalization must include well-defined strategies to facilitate the interaction for people with diverse motor abilities. Since each Exergame includes a set of various body movements (e.g., drag and step, row and navigate), health professionals should be able to activate/deactivate individual body gestures depending on users' abilities.
- Cognitive tasks: the inclusion of more cognitive-demanding activities in conjunction with physical exertion might enhance health benefits and increase engagement, and consequently the likelihood of long-term adoption of this technology [168].
- Parametrization: the inclusion of multiple game parameters might help to facilitate activities' personalization regarding fitness domains and training dimensions. By defining a set of game parameters, the difficulty will be controllable allowing a more precise adaptation to the specific motor and/or cognitive skills.

4.3.2 Modification to the Exergames

Several changes were made in each Exergame aiming at incorporating both the RCD in-sights and Personas as well as the feedback data obtained in the playtesting. The most relevant changes are the addition of multiplayer options, instructive videos for in-time feed-back, and the personalization of each game menu. *Table 5* summarizes the changes made in each game after the iteration process.

Table 5. Changes carried out along the iteration process with the Portugal Tour Exergames.

Exergame	First implementation	Implementation after iterations
Grape Stomping	a) Single player; b) No instructions supplied; c) Pull and step; d) Only physical challenge; e) Non-parameterized winemaking process.	a) Single and Multiplayer (collaborative or competitive). Users are situated in different tanks; b) A tutorial providing in-time videos for feedback in the drag, stepping and lateral movements; c) Pull and/or step; d) Physical and cognitive challenges. Cognitive challenges were added using wine recipes; e) The treadmill velocity and the number of steps for winemaking parameters were added for difficulty modulation.
Rabelos	a) Single player; b) Instructions used images and were displayed at the beginning; c) Rowing and lateral boat displacement; d) Non-parametrized course; e) Pre-defined calibration for the floor.	a) Single and Multiplayer (collaborative or competitive). Users embody different boats; b) A tutorial providing in-time video feedback for the rowing, lateral displacements and barrels pick up gestures; c) Optional rowing and/or boat direction. Both can be automated by the system; d) Docks and rocks separation distance was added as game parameters for difficulty modulation; e) A calibration module was added to the project allowing an initial configuration of the spatial parameters for the position tracking.
Exerfado	a) Single joint interaction; b) Only one song was used; c) Non-parametrized gestures and song-tracks; d) No clear audiovisual feedback supplied.	a) Waist and feet tracking; b) MIDI files can be added; c) 4 parameters addressing arm extension, the time between notes, note sliding time and song track can be used to personalize the experience; d) A swipe gesture visual feedback was added in conjunction with audio feedback for punishment and reward.

Toboggan Ride	a) Single player; b) No instructions supplied; c) Direction control only with trunk lateral flexions; d) Non-parametrized course. Only objects to collect; e) Pre-defined calibration for the floor; f) Male avatar.	a) Single and Multiplayer (collaborative or competitive). Users placed in different toboggans; b) A tutorial providing in-time videos for feedback on the car's acceleration and deacceleration as well as for the car's direction; c) Lateral displacements were added to control the direction of the car; d) We added elements to avoid in the scene and a control parameter for the distance between the objects to collect; e) A calibration module was added allowing an initial configuration of the spatial parameters for the position tracking; f) Male and female avatars.

After this iteration process, the graphical elements of each Exergame were improved. The GUI was standardized across all the menus, including the in-time feedback for gesture achievement and a panel for text and video instructions. We included English and Portuguese languages for the initial configuration menu, a tutorial, in-time instructions (they appear sequentially to support users along the experience) and a final screen with the game metrics. *Figure 13* shows screenshots of the final version of each Exergame.

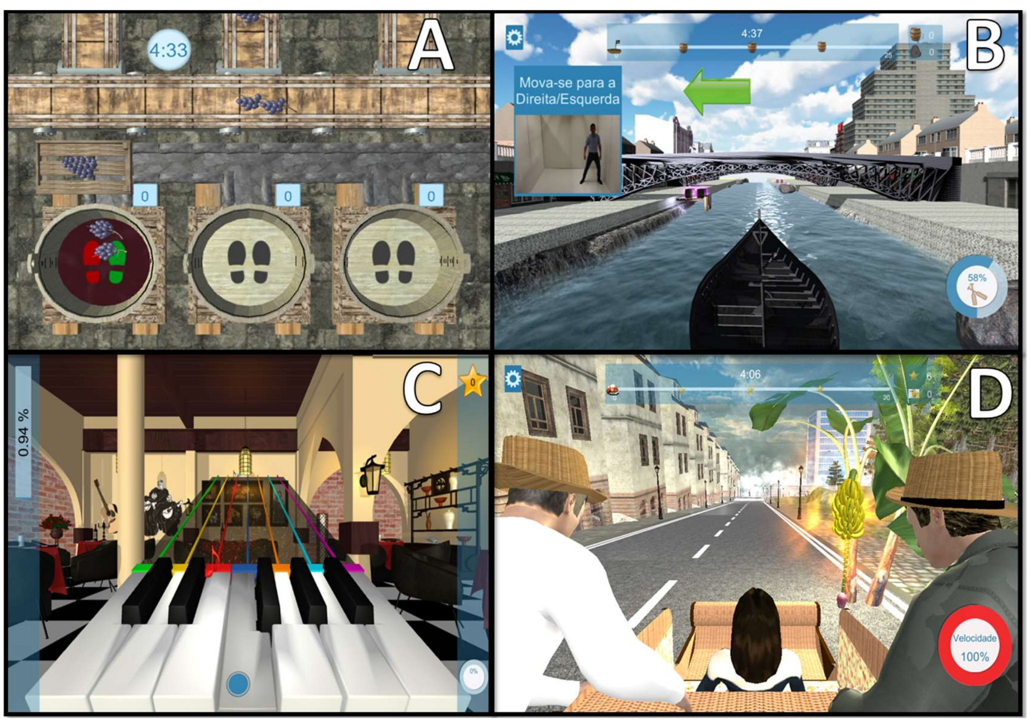


Figure 13. Screenshots of the final Exergames. A. Grape Stomping, B. Rabelos, C. Exerfado, and D. Toboggan Ride.

Finally, *Table 6* summarizes the Exergame parameters that can be set to adjust the difficulty of the fitness training dimensions. The table shows how all fitness domains are covered by specific sets of game parameters.

Table 6. Summary of the complete set of Exergame parameters, which can be modified to cover motor ability, cardiorespiratory, and muscular strength fitness domains.

Exergame	**Motor Ability**			**Cardio Respiratory**	**Muscular Strength**		
	Balance	**Agility**	**Flexibility**		**Upper**	**Lower**	**Trunk**
Grape Stomping	Pose, stepping, step height, side movements	Treadmill velocity, recipes, distractors (%)	Pose, step height	Duration, pose, stepping, step height, dragging	Dragging	Pose, number of steps per bunch	None
Rabelos	Pose, boat direction	Pose, separation of rocks	Pose, boat direction, rowing mode, separation of docks	Duration, boat direction, rowing mode, separation of rocks.	Rowing mode, separation of docks	Pose, boat direction, separation rocks.	Pose, separation of the rocks
Exerfado	Tracking mode	Time between notes, note sliding time	Arm extension, tracking mode	Duration, time between notes, note sliding time	Arm extension	Tracking mode	None
Toboggan Ride	Pose, car direction mode	Pose, objects separation	Pose, objects separation	Duration, car direction mode, objects separation	None	Pose, car direction mode, objects separation	Pose, car direction mode

4.4 <u>Conclusion and Guidelines for context-aware Exergame design</u>

Past paradigms for the development of fully-engaging videogames aimed at exercise promotion and rehabilitation failed to provide strong elements for sustainable motivation [22]. They failed at both system personalization [8] and contextual information integration [169], consequently restricting the impact of Exergames. Our study emphasizes the need for a paradigm shift to generate more engaging and usable Exergames for older adult populations through the combination of multiple HCI techniques.

After analyzing our main results of designing Exergames through human-centered design and iterative approaches, we propose a set of guidelines that intend to summarize our efforts in constructing a methodology for Exergame design and development for exercise promotion in older adults.

a. Focus on human-centered approaches
    - Use agile software development and standardized methodologies (e.g., RCD).
    - Be sure of having user's models to aid the communication process (e.g., Personas).
    - Go for the short and frequent field inquiries instead of a long and unique interview.
    - Investigate game preferences and interaction limitations of the target population to enrich the game design process frequently.
b. Increase emphasis on fun experiences through gamification elements
    - Balance attractiveness and effectiveness by interweaving storytelling with game mechanics [170].
    - Exploit the familiarity of contextualized activities and factors (e.g., wine industry in Portugal).
    - Consider elaborating a game design and specifications document before starting the development process.
c. Improve collaboration with sports and healthcare professionals
    - Include professionals actively in each project stage.
    - Ask healthcare professionals to summarize and list the health requirements for the gamified system.
    - Promote spaces and situations to boost interactions between technologists, and sports and healthcare professionals (e.g., game jams).
    - Comprise strategies to integrate technology in sports facilities and healthcare institutions beyond the research phase.
d. Rapid digital prototyping and fast iteration
    - Investigate existing software and methodological tools to accelerate the prototyping process before starting a development process from scratch.
    - Include multiple playtesting sessions to evaluate game design elements with end-users before the research trials.
    - Contemplate at least three generations of prototypes in the project timeline.

5 Long-term Validation Study of the Contextually-Rich Exergames

In this chapter, we show the methods, tools and experimental design used to evaluate the contextually-rich Exergames designed and documented in chapter 4. Preliminary results are exposed detailing how 3-months of exercising with an Exergame-based program for multidimensional training can produce benefits regarding functional fitness and physical activity patterns in a group of older adults. The here presented results constitute a demonstration of the effectiveness of our human-centered Exergame design approach.

After reviewing the studies evaluating the long-term effects of Exergaming in older adults, here we enumerate a set of previously identified weaknesses:

A. 5 of 8 studies utilized commercial-available Exergames, which have a limited level of personalization, and its use with older population has been widely criticized [171].
B. From an ethical perspective, studies that used only Exergaming as exercise therapy generate controversy since it is depriving users of their regular exercise and exposing them to a new and no yet validated exercises [172].
C. No studies were found wherein measured and perceived physical activity levels had been contrasted in longitudinal interventions with older adults.
D. The replicability of those studies using custom-made Exergames remains a major challenge since the setup is difficult to reproduce and the tools and games are usually unavailable [15].

To fill those gaps, this section describes our efforts towards evaluating the long-term effects of a training program with the custom-made Exergames previously described. We designed a randomized controlled experiment with a group of active older adults combining several metrics to identify the health benefits of exercising with Exergaming approaches using standardized fitness tools and tests. Functional fitness, and measured and perceived levels of physical activity are used to quantify the effects of exercising with a multidimensional fitness training routine that follows the ACSM recommendations in a 3-months intervention. Therefore, this longitudinal study compares combined (traditional + Exergaming) training with traditional physical activity in a group of active older adults from a local senior gymnasium. We carried out the Exergaming training in a very simple setup that uses floor projection as playground and some of the tools here described are freely available at:
https://neurorehabilitation.m-iti.org/tools/en/

Our research attempts at investigating the longitudinal effects of the multidimensional and combined Exergaming training on senior's functional fitness and physical activity patterns. The hypotheses here proposed established improvements on the fitness levels produced by training with our custom-made Exergames once compared with traditional exercise methods.

5.1 Methods

5.1.1 Exergames System setup and

The set of Exergames reported in chapter 4 was used to provide a multi-dimensional fitness training program [173]. Although each Exergame has been designed to cover a main training domain (e.g., aerobic endurance, upper/lower strength, and motor ability), several game parameters were used to aid the content personalization in meeting senior's needs. The Exergames were installed at the facilities of the local senior gymnasium.

System Setup
To create a digital playground able to demand measurable amounts of exertion in older users, we used a floor projection setup on a white 2.5m x 3.0m PVC surface. Player's position tracking is performed by using the KinectV2 sensor (Microsoft, Washington, USA), which captures 25 joints anatomically distributed. Each Exergame utilizes a different combination of joints for tracking body gestures that are used in the game mechanics.

Exergames
Grape Stomping (Aerobic, Figure 14-A): based on the stepping exercises that are widely used for aerobic training in older adults [35], this Exergame proposes a grape stomping activity aiming at producing virtual wine. The game variables that can be adjusted in the *Grape Stomping* Exergame are: step height, treadmill velocity and the addition of recipes. The game performance can be measured through the number of litters produced and the number of steps along the session.

Rabelos (Strength, Figure 14-B): this Exergame encourages people to row in a virtual Rabelos boat to create an upper-body strength training experience. Obstacles such as rocks are placed along the river to force people to move laterally while the rowing mode (light, hard), boat direction mode (trunk, lateral movements) and the separation of docks can be personalized in this Exergame. Game performance is measured through the total number of barrels collected minus the hit rocks.

Exermusic (Motor ability, Figure 14-C): this Exergame uses a game mechanic based on musical notes to exercise lower-limb strength and flexibility. Exermusic can be parametrized by changing the tracking mode (waist or foot), MIDI soundtrack, the time between notes and note sliding time. The percentage of notes and bonus notes collected are used to compute the game performance.

Toboggan Ride (Motor ability, Figure 14-D): this Exergame places players in a virtual wicker sledge sliding downhill driven by two human pilots. The *Toboggan Ride* Exergame trains overall balance by exercising postural stability and trunk muscular strength. Game parameters such as car direction mode (trunk or lateral movements), trunk angle trigger and distance between bananas can be modified. Finally, the game performance is measured through the number of bunches of bananas collected minus obstacles hit.

Exerpong (Aerobic, Figure 14-E): an Exergaming adaptation of the classic pong was used to provide a fast-paced game aiming at training aerobic endurance [51]. Players have to control a virtual paddle using lateral movements while a ball is bouncing around. Layers of bricks are constantly added in random configurations and players have to break them by bouncing the ball. The goal of the game is to avoid losing balls while constantly hitting the ball and getting points by breaking the bricks. Game parameters such as ball speed and size, and paddle size can be modified. Game performance is measured through the number of bricks broken and the balls lost.

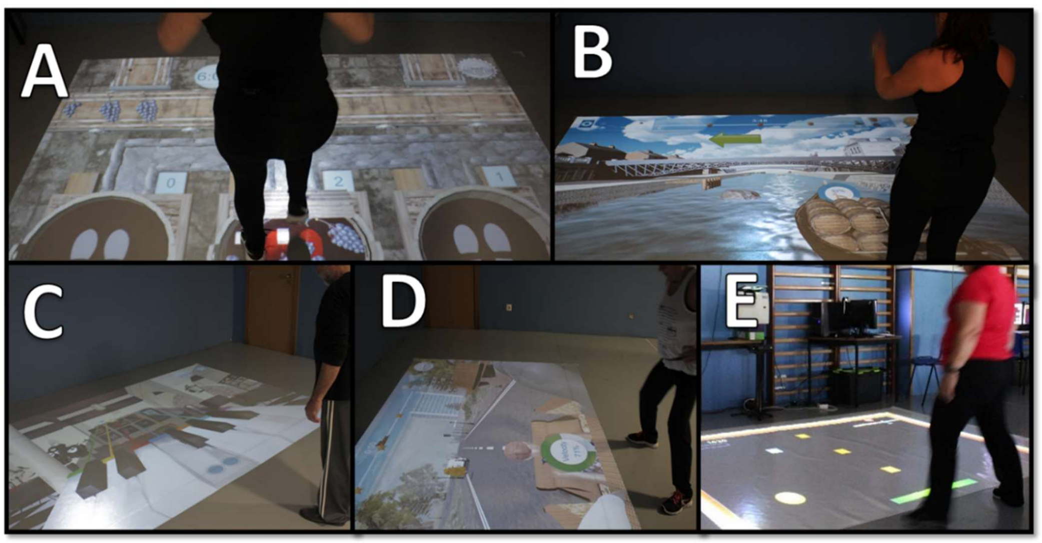


Figure 14. The set of Exergames used in the *Exergame* group. Grape stomping (A) and Exerpong (E) train aerobic fitness. Rabelos (B) trains upper and lower limbs strength while the Exermusic (C) and Toboggan Ride (D) train motor ability.

5.1.2 Participants

A group of 37 active community-dwelling older adults (26 females, ages M=68.6, SD=4.5 years) was randomized to participate in a 3-months length study. During the enrollment process, potential participants (n=233) were previously selected by the gymnasium sports science professionals considering their regularity in attending the training sessions and their availability for the study. After the assessment, 196 were excluded. A detailed CONSORT flow diagram is shown in *Figure 15*.

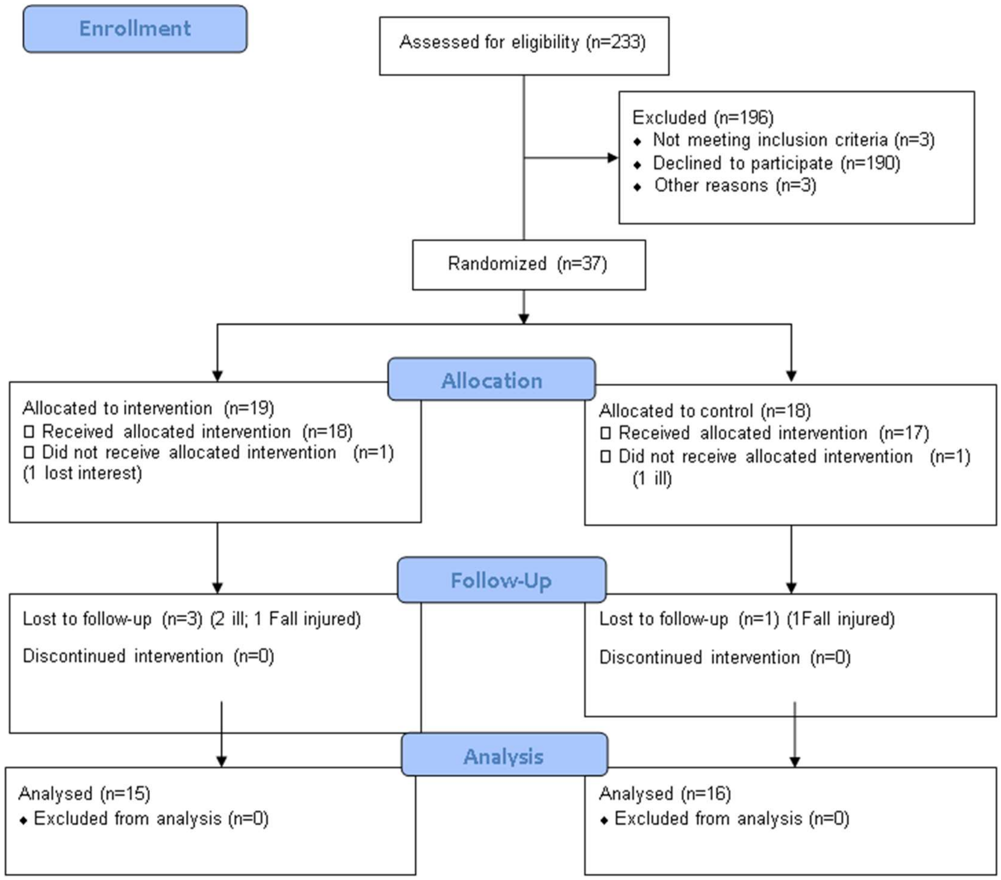


Figure 15. CONSORT flow diagram showing the phases of the study's randomization from enrolment to the analysis stage.

A local senior gymnasium was chosen considering the size (average 500-600 older adults), proximity with the investigators and feasibility regarding space and equipment. Participants were informed about the study protocol, procedures, and assessments. Participants provided an inform consent before starting the study and scheduled their availability to make exercise. As inclusion criteria we used: i) seniors in a range of age from 60 to 75 years old, ii) voluntary motivation to participate in the study (no economic reward was offered), iii) no cardiac diseases based on self-reports and historical data in the gym, iv) cognitive performance sufficient to understand the procedure, game rules and study goals as assessed by the *Mini-mental State Examination (MMSE)* that covers orientation, registration, attention, and calculation, recall, language and praxis functions [174], and v) minimum risk of falling measured by standardized fitness tests.

Table 7. Baseline characteristics of the study volunteers.

Characteristics	***Control* Group (n=18)**	***Exergame* Group (n=19)**
Age, years (mean ± SD)	69.8 ± 3.9	67.4 ± 4.8
Sex, M/F (n)	4/14	7/12
MMSE (mean ± SD)	26.2 ± 6.6	27.2 ± 1.8

5.1.3 Outcome Measures

In this particular experiment, we were interested at studying functional fitness and physical activity parameters. Subjective and objective measurements are used to better understand levels of physical activity during all the training routines while standardized fitness tools are used for the functional fitness and assessed in particular moments.

Functional Fitness Assessment

Senior Fitness Tests (SFT): is a simple and comprehensible method for assessing functional fitness in adults ages 60 and older [146]. The SFT contemplates seven different tests covering lower and upper body strength, aerobic endurance, lower and upper body flexibility, agility, and balance. The tests are described as follows:

- Chair stand test (CST): to assess lower-body strength via counting the number of full stands from a seated position with the arms folded across the chest, completed in 30 seconds.
- Arm curl test (ACT): to assess upper-body strength by counting the number of biceps curls that can be completed in 30 seconds holding a hand weight of 2.3 KG (3.6 Kg for men).
- Chair sit and reach test (CSAR): to assess lower-body flexibility measuring the number of centimeters between extended fingers and the tip of the toe while seated at the front of a chair with a leg extended and hands reaching toward toes.
- Back scratch test (BST): to assess upper body flexibility, requires users to reach with one hand over the shoulder and with the other hand up the middle of the back. Then, the distance between the extended middle fingers is measured.
- 8-Foot up and go test (FUG): to assess dynamic balance and agility by counting the number of seconds a user requires to get up from a seated position, walk precisely 2.4 meters (8 feet), turn, and return to the seated position.
- 6 minutes walk test (MWT6): evaluates aerobic endurance by counting the number of meters that can be walked in 6 minutes around a 45.7 meters course.
- Handgrip strength test (HANDG): simple and effective method to evaluate hand strength (maximum isometric strength) via measuring the force (in Kg) of user's dominant hands while squeezing a dynamometer during 5 seconds.

Fullerton Advanced Balance (FAB): is an elementary test to evaluate both dynamic and static balance in older adults under different situations in order to identify balance deficits. The ultimate goal of the test is to detect highly active older adults who are at an increased risk of falling [175]. In the short version, users are encouraged to carry out four different activities: i) reaching forward to object (sensory systems, neuromuscular response synergies), ii) walk 10 steps with head turns (sensory systems and strategies – vestibular, vision, adaptive mechanisms), iii) stand on one leg (musculoskeletal components, anticipatory mechanisms) and iv) stand on foam, eyes closed (internal representations). A total score is computed as the sum of each score according to the user's performance (0 min – 16 max).

Physical Activity

*Perceived intensity of physical activity: t*he *OMNI* rating of perceived exertion pictorial scale is a 0 to 10 graphical scale (see *Figure 16*), which allows getting a subjective measure of physical activity intensity levels [6]. This pictorial scale is used right after each training session to provide subjective feedback about the exercise intensity and overall exhaustiveness.

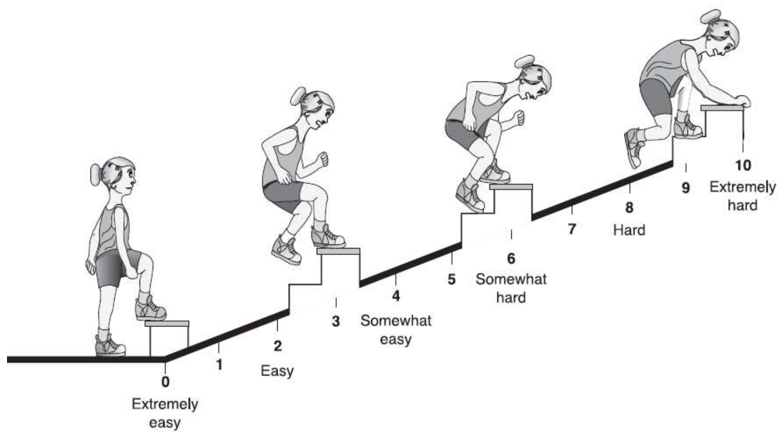


Figure 16. OMNI: Pictorial rating of perceived exertion (Taken from [6]).

Measured physical activity: to collect kinematic information during the exercises, a three-axial accelerometer embedded in the research-grade WGT3X-BT ActiGraph's activity monitor (Actigraph, Florida, USA) was used. The actigraphy sensor was placed on the user's waist providing raw acceleration data at 30 Hz sampling frequency using epochs of 30 seconds during the 40 minutes of multidimensional physical training. By using a standalone software created by the sensor manufactures (Actilife 6.10), the time participants spent exercising at MVPA intensities can be computed.

5.1.4 Experimental protocol

Participants were randomly allocated to two different groups, which were equivalent considering the main components of the fitness training routine: Frequency, Intensity, Time and Type (FITT) [6]. Exercise frequency was defined as twice per week while the intensity was intended to keep users exercising at MVPA levels. The time or duration of the training was defined as one hour per session. Finally, the type of training routine was designed considering a multidimensional and multi-stage workout:

- 5-10 minutes of warming-up (stretching, muscular preparation).
- 20-25 minutes of multidimensional physical training (intense exercise).
- 10 minutes of cooling down, stretching stage (muscle relaxation).

Particularly, the multidimensional physical training stage (20-25 minutes) followed the ACSM guidelines for older adults [35] considering a training that covers three key fitness areas: (1) cardiorespiratory, which represents 50% of the total session time; (2) muscle strength/endurance, ranging between 20 to 30% of the total session time, depending on the week plan; and (3) motor ability (neuromotor training), with the same preponderance. No equipment (i.e., air pads, resistance bands, weighted balls) was used in the training. A total of 24 sessions were delivered over 12-consecutive weeks.

The difference between the groups lies in the exercise modality chosen for the multidimensional physical training stage, as described:

A. *Control (c*onventional training): specific functional fitness exercises were chosen to be performed via group training sessions led by a sports science professional. The exercises cover (but were not limited to) marching in place, step touches, stepping on pads, and squats.
B. Exergame (conventional training and Exergaming): our intervention group consisted of a combined training program with traditional exercise and Exergaming. Conventional exercises addressed the same exercise routine as in the *Control* condition, and it was delivered with a frequency of once per week. Additionally, a training regime with Exergames was delivered with the same frequency and duration, therefore completing a combined workout program of two hours weekly (time-matched with the *Control* condition).

To deliver high levels of exercise personalization during conventional training, participants of both *Control* and *Exergame* groups were divided into four smaller subgroups (two per condition).

Four different assessment moments were defined to register the baseline status and changes in the functional fitness during and after the intervention.

- **A**: baseline. The multipurpose baseline assessment was carried out before starting the study. We applied both the SFTs battery and the FAB scale to evaluate the functional fitness and balance. All tests were performed at the senior gym facilities in controlled environments for around two weeks before starting the study.
- **B**: intermediate - week #6. Changes in the functional fitness were measured through the SFT battery and the FAB test.
- **C**: final – week #13. The same as in the second assessment.
- **D**: follow-up – week #17. The same as in the second assessment.

We used the week number zero (right after the baseline assessment) to familiarize the groups of older adults with the new exercise routines, connectivity of the activity trackers, a rating of perceived exertion and to fix some possible bugs in the Exergames. Mainly, we were interested in having an introductory session with the participants of the Exergaming group to formally explain them the particularities of each game. The exercise training was carried out in a suitable room of the local senior gymnasium. An A1-size OMNI pictorial scale was printed and placed in one of the walls of the exercising room. Users used this scale immediately after the workout to rate the level of exhaustiveness they felt during the session. For the *Control* group, the perceived exertion was rated after each training session and so was the conventional training in the *Exergame* group. In the Exergaming session of the *Exergame* group, the perceived exertion was rated after the interaction with each game, and the final score was averaged. This subjective data collected with the OMNI scale was posteriorly used to adjust the intensity levels of the training sessions by adapting the game variables in each Exergaming session or the number of repetitions and the pace of the conventional exercise. The adaptation strategy was based on the trainer's criteria always aiming at maintaining the intensity levels recommended for this population (5-8 moderate to vigorous) [35]. The data collected during this week was not used in the final analysis. Since both *Exermusic* and *Toboggan Ride* games are focused on balance training, we alternately used them every week.

Data processing and analysis

Data normality was checked using the Kolmogorov Smirnoff test, revealing non-normal distributions. Therefore, non-parametric analysis was carried out using the Mann-Whitney U test to measure the statistical difference between the groups for both measured and perceived levels of physical activity. The Friedman test was used to find differences between all assessment moments for each condition separately, and a post hoc analysis was done between pairs of moments using the Wilcoxon signed-rank test. A one-tailed analysis was used considering the above-mentioned hypothesis, this is better fitness levels at the assessment moment C once compared with moment A as well as lower fitness levels in moment D once compared with C.

5.2 Results

5.2.1 What are the benefits in terms of functional fitness of exercising with a combined multidimensional Exergaming program?

The SFT battery was used to evaluate the functional fitness domains trained in the study. The Friedman test revealed that upper-body flexibility (BST) and dynamic balance and agility (FUG) were significantly affected throughout the assessed moments in the *Control* condition (see *Table 8*).

Table 8. Friedman test results for the *Control* condition revealing changes on the SFT battery between assessment moments.

	CST	ACT	CSAR	BST	FUG	MWT6	HANDG
N	15	15	15	15	15	13	15
$\chi 2$	3,470	1,599	4,360	25,591	32,758	,727	3,880
df	3	3	3	3	3	3	3
p	,325	,660	,225	**< ,001**	**< ,001**	,867	,275

A post hoc analysis revealed a significant decrease of BST scores in the D moment (*Mdn*= -8.5) once compared with the C moment (*Mdn*= -2.8), z = -3.51, p < 0.025, r = -0.24 (see *Figure 17*).

Results from Senior Fitness Test Battery

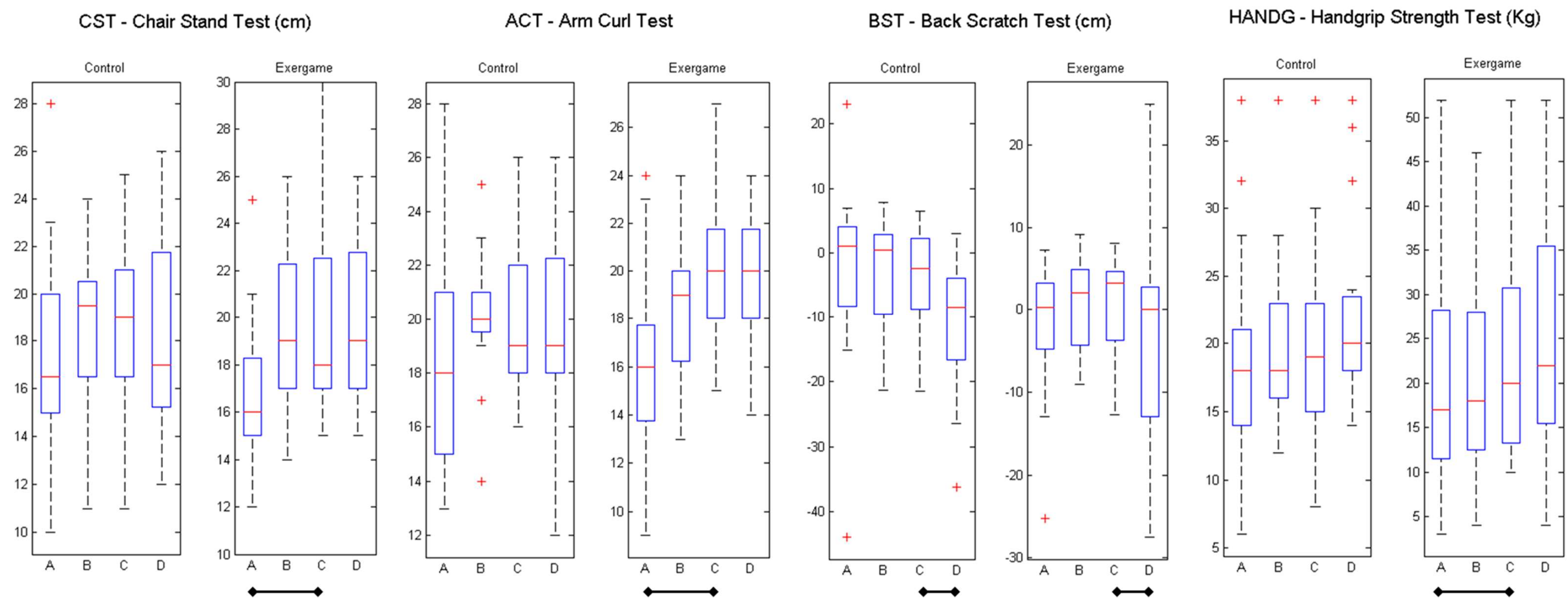


Figure 17. Results from the Senior Fitness Test battery for the assessment moments A, B, C and D, and the *Control* and *Exergame* conditions.

Moreover, the Friedman test also revealed significant effects throughout the assessment moments in the *Exergame* condition. All the tests excluding the CSAR (lower-body flexibility) and the MWT6 (aerobic endurance) exposed significant differences between the four assessment moments (see *Table 9*).

Table 9. Friedman test results for the *Exergame* condition revealing changes on the SFT battery between assessment moments.

	CST	**ACT**	**CSAR**	**BST**	**FUG**	**MWT6**	**HANDG**
N	15	15	15	15	15	14	15
χ2	8,127	11,553	6,423	18,103	14,534	2,395	9,638
df	3	3	3	3	3	3	3
p	**,043**	**,009**	,093	**,000**	**,002**	,495	**,022**

Again, a post hoc analysis revealed significantly better performances for the *Exergame* condition on: i) lower-body strength (CST), $z = -2.41$, $p < 0.025$, $r = -0.4$, at moment C (*Mdn*=18.5) once compared with moment A (*Mdn*=17.0), ii) upper-body strength (ACT), $z = -2.60$, $p < 0.025$, $r = -0.43$, at moment C (*Mdn*=18.0) once compared with moment A (*Mdn* = 19.0), iii) upper-body flexibility (BST), $z = -2.41$, $p < 0.025$, $r = -0.44$, at moment C (*Mdn*=3.3) once compared with moment D (*Mdn*=0.0) and iv) hand strength (HANDG), $z = -2.63$, $p < 0.025$, $r = -0.43$, at moment C (*Mdn*=19.5) once compared with moment A (*Mdn*=15.5). Boxplots of each fitness domain can be seen in *Figure 17*.

The FAB total score was used to quantify the effects of the *Exergame* training on participant's balance and to compare it against the *Control* condition. Overall, the dynamic and static balance were significantly affected by the assessment moment, $\chi2$ (3) = 14.02, $p < 0.05$.

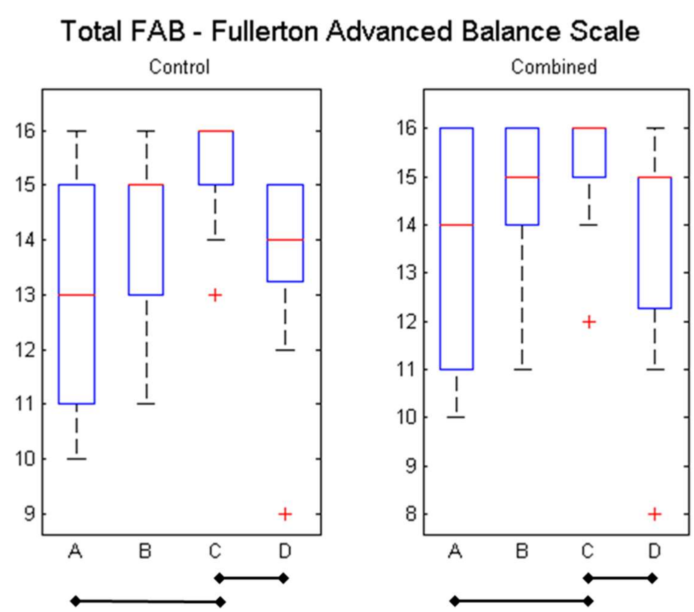


Figure 18. Boxplot representing the FAB total scores comparing the Control and Exergame conditions along the four assessment moments.

A post hoc analysis reflected differences between assessment moments (A-C, C-D) for both *Control* and *Exergame* conditions as follows: i) better FAB scores, *Control*: $z = -2.81$, $p < 0.025$, $r = -0.46$, *Exergame*: $z = -2.73$, $p < 0.025$, $r = -0.44$, for the C moment (*Control*: *Mdn*=16.0; *Exergame*: *Mdn*=16.0) once compared with the A assessment moment (*Control*: *Mdn*=13.0; *Exergame*: *Mdn*=14.0) and ii) better FAB scores, *Control*: $z = -3.08$, $p < 0.025$, $r = -0.52$, *Exergame*: $z = -2.67$, $p < 0.025$, $r = 0.45$, for the C moment (*Control*: *Mdn*=16.0; *Exergame*: *Mdn*=16.0) once compared with the D assessment moment (*Control*: *Mdn*=14.0, *Exergame*: *Mdn*=15.0) as shown in *Figure 18*.

5.2.2 How effective in terms of physical activity is exercising with a combined multidimensional Exergaming program?

Effectiveness in physical training was quantified as the total amount of MVPA in minutes that participants spent in the individual sessions of 40 minutes long. A session-by-session plot is showed in *Figure 19*, which reflects the behavior of the MVPA along the 24 sessions comparing the values from both the *Control* and *Exergame* groups. Overall, participants in the *Exergame* group were always spending more time at MVPA levels of exercise intensity as compared with the *Control* group.

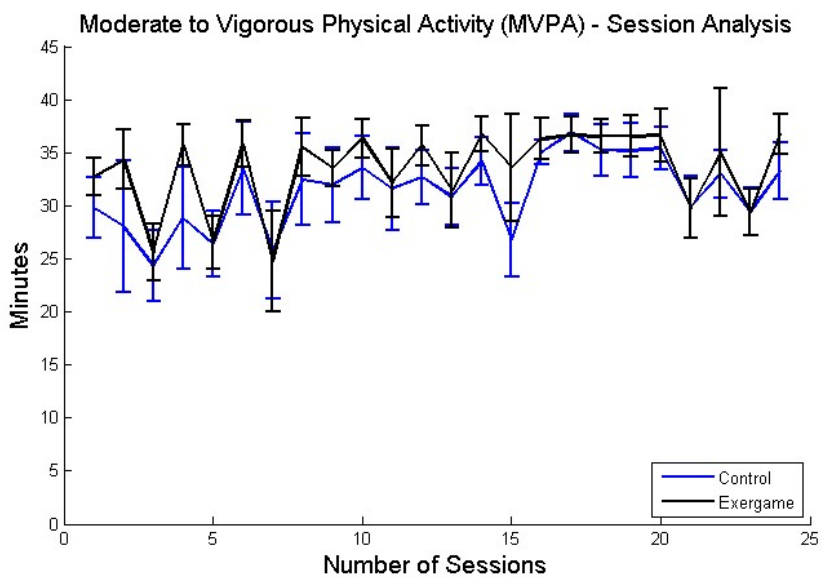


Figure 19. Session-by-session plot, showing the minutes participants spent in the MVPA levels of intensity for each exercise modality (*Control* and *Exergame*). In the *Exergame* group, odd sessions are conventional exercise while evens are Exergaming sessions.

The Mann-Whitney statistical test revealed that participants in the *Exergame* group (*Mdn*=34.5) spent significantly more time of MVPA once compared with participants in the *Control* group (*Mdn=32.5*), $U = 47.3 \times 10^3$, $z = -6.56$, $p < 0.05$ (*Figure 20*).

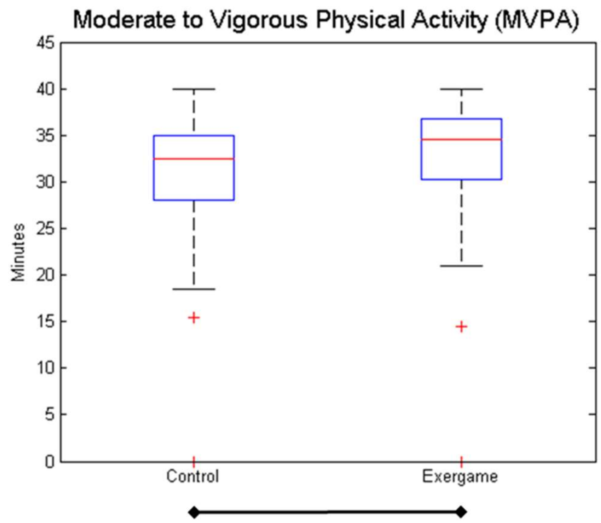


Figure 20. Boxplot depicting the MVPA levels of exercise intensity for the 40 minutes sessions of *Control* and *Exergame* groups.

Similarly, to the MVPA session-by-session plot, *Figure 21* shows the long-term behavior concerning the ratings of perceived exertion. It can be noticed that, again, the OMNI values perceived by participants in the *Exergame* group were always higher than the *Control* group, which is consistent with the measured MVPA levels.

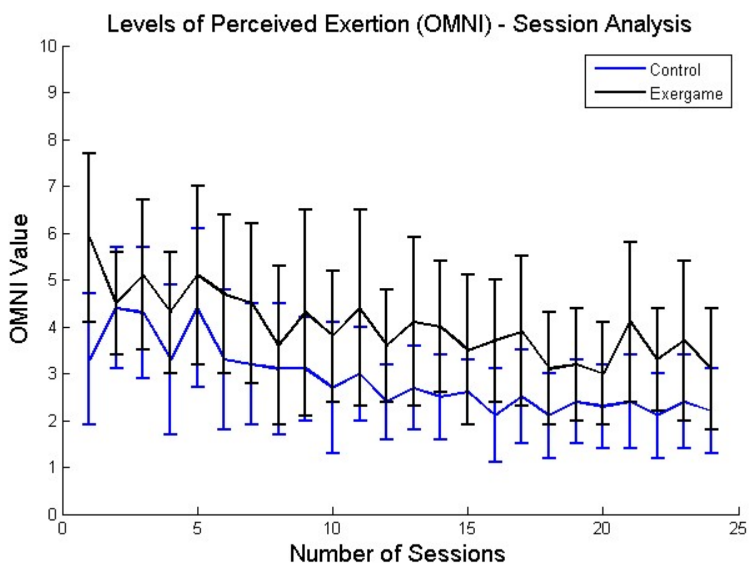


Figure 21. Session-by-session plot, showing the ratings of perceived exertion for each exercise modality (*Control* and *Exergame*) measured through the OMNI pictorial scale. In the *Exergame* group, odd sessions are conventional exercise while evens are Exergaming sessions.

Additionally, the OMNI rating of perceived exertion was used to subjectively contrast the measured levels of physical activity (*Figure 22*). Statistical analysis revealed that participants in the *Exergame* group (*Mdn*=4.0) differed significantly from the *Control* group (*Mdn=3.0*) in terms of levels of perceived exertion levels, U = 38.7 x10^3, z = -10.5, p > 0.05.

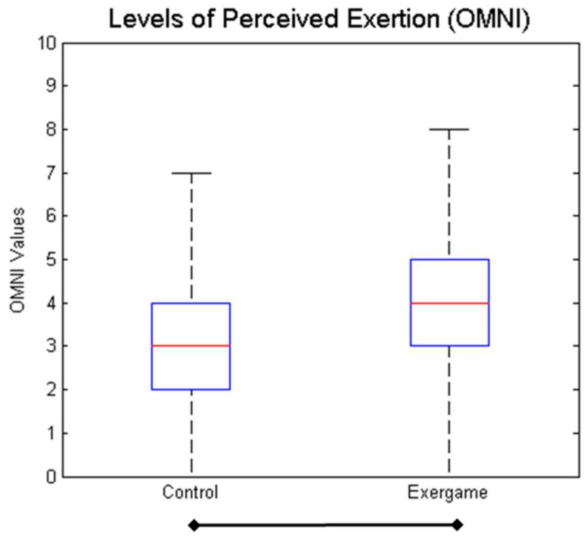


Figure 22. Boxplot depicting the differences between the *Control* and *Exergame* groups in terms of the ratings of perceived exertion measured through the OMNI pictorial scale.

5.3 Conclusion and Discussion

We demonstrated that multidimensional training that includes custom-made Exergames has the potential to enhance particular functional fitness (such as strength, flexibility, and balance) in active older adults compared to an exclusive conventional training program. Interestingly, the Exergaming program showed performance regarding physical activity levels that are aligned with the recommendations for this population. Participants reported their perceived levels of exertion according to their levels of MVPA along the 3-months. Thus, after applying human-centered design methods for Exergame design and evaluating their impact on a longitudinal and controlled experiment, we recommend multidimensional training programs through Exergaming to enhance particular fitness domains in older adults. Such programs have the potential to counterbalance the effects of aging regarding mobility, independence, and quality of life.

Our findings are aligned with previous research showing the value of modes of training that incorporate various human-centered designed Exergames, aiming at covering several fitness dimensions in the older population [24], [176]. First, functional fitness parameters evaluated through standardized tools (e.g., SFT, FAB) illustrated how including Exergaming in training programs may produce benefits that are equivalent to those encountered in conventional fitness methods. More interestingly is seeing how participants in the *Exergame* condition revealed improvements where the conventional methods were unable. Namely, both lower and upper body strength fitness tests (CST and ACT) were aligned with our initial hypothesis of having significant improvements at the end of the intervention. Here, the

importance of creating equivalent conditions allow us to conclude that the complementarity of multidimensional Exergaming programs can boost the effectiveness of exercising through traditional methods. Maybe the best results were found in the balance assessment with the FAB scale, showing the equivalence of the conditions again to produce the desirable functional fitness outcomes. All in all, it has been shown that improvements in the functional fitness domains (e.g., strength, flexibility) are intrinsically related with the performance of daily life activities and the level of independence in older adults [32], [155].
Undoubtedly, the fun and enjoyment of having a diverse set of contextually-rich Exergames encouraged participants to push their exercise intensities beyond what they believed was possible. Also, through this diversification, the exercise routines might be transformed into a less tedious activity allowing more engaged participation along more extended interventions. In a short focus group carried out in the last month with the participants of the *Exergame* group, we asked them about their levels of satisfaction and willingness to participate in future interventions. It was clear that their levels of engagement with the combined training were highly related to their commitment to finish the 3-month program. At that moment, several participants had already developed strategies to score more in each game and to keep scoring better and better after each session. This "competition against themselves" mode, produces psychological effects that are difficult to achieve during conventional training methods with older adults: while counting the number of exercise repetitions can be tiresome, stomping grapes with the goal of producing more wine for the winery might not be [177].

Furthermore, although both *Control* and *Exergame* conditions exhibited very similar results regarding physical activity patterns, it is clear that Exergaming adds a valuable and measurable effect with regard to the way seniors exert and make physical activity in the senior gymnasium. Accelerometer data revealed statistically higher levels of MVPA in the *Exergame* routine compared with conventional exercise in similar groups of seniors. Some previous studies have reported the impact of Exergaming in the time players spent exercising at MVPA levels in young adults [178] and children [179]. However, to our knowledge, this is the first longitudinal study reporting MVPA exertion in the older population. The similar MVPA values in both *Exergame* and *Control* conditions illustrate how combined strategies can create different routines without losing efficiency in the physical activity. Consistently, both measured and perceived levels of physical activity showed participants in the *Exergame* condition experiencing the most demanding training routine regarding physical exhaustion.

We highlight the importance of using custom-made Exergames rather than commercially-grade consoles to promote exercise in older adults. This has been identified as one of the most critical limitations of Exergames since the older population is diverse and complex in terms of health conditions [15], [180]. Our approach included a set of highly personalized Exergames especially designed to cover multidimensional training in older adults. Furthermore, the importance of accurately quantifying the physical activity and characterizing human movement during Exergaming interventions to show not only Exergames' "attractiveness," but an "attractive and effective" training modality for older adults [156]. This particular study also contributed to unveil the differences of measurements through research-grade activity trackers and perceived exertion scales in quantifying the physical activity levels of older adults using custom-made Exergames.

With this study, the effects of human-centered Exergaming design on standardized fitness metrics and long-term physical activity patterns are evidenced, exposing measurable benefits of including multidimensional and highly personalized Exergames in fitness training for older adults. In summary, chapters 4 and 5 addressed the first research question by clearly defining methodologies to integrate human-centered techniques in the design of customized Exergames for seniors and evidencing the effectiveness regarding fitness validated metrics of its longitudinal use.

6 Closing the Loop with a Cardiorespiratory Adaptive Exergame

In this chapter, the pathway for integrating biocybernetic adaptation technologies in cardiorespiratory Exergaming training is described. We used an experimental Exergaming version of the classic pong called Exerpong as a playful arena to stimulate endurance training in older adults. Firstly, a physiological characterization study was carried out to discover how game variables (e.g., ball velocity, paddle size) can modulate cardiac and arousal responses of users during a training session. Posteriorly, a biocybernetic loop that uses real-time HR data to adapt the Exerpong difficulty was implemented and evaluated in a pilot study that measured the cardiovascular effectiveness of this physiologically adaptive approach. Then, we moved to a more controlled and extended study that investigated the cognitive, cardiovascular, functional fitness and game user experience effects of training with the cardio-adaptive Exerpong during six weeks.

This section reports the entire process carried out to integrate the biocybernetic adaptation technology in an experimental Exergame designed for cardiorespiratory training in older adults (Exerpong). After applying human-centered design methods in our game design process, we moved to a real-time adaptation approach that might enhance the body responses by integrating physiological awareness into the Exergaming core. The main motivation here is to improve the session-by-session cardiovascular effectiveness of the training with Exergaming via persuading participants to exert in their individual recommended zones defined by the target HR concept. Such improvements might maximize the well-known benefits of CRF training in older adults by optimizing the heart responses while training without over exercising it, thus avoiding risky situations. Although the biocybernetic adaptation technique has been well-described [29], [86], its application in Exergames to promote physical activity in older adults is still unknown. Involving the (aged) human in the loop possesses countless challenges regarding unpredictable physiological responses as consequence of age-related health declines and medicaments (among many other factors). Thus, this chapter is dedicated to address the second research question proposed that outlines the suitability of the BL construct to enhance the cardiorespiratory effectiveness of adaptive Exergaming. In all the experiments described in this chapter, we used different versions of the Exerpong, which used a floor projection setup to provide the transformation from a videogame to an Exergame.

6.1 Exerpong Cardiovascular Characterization Study[10]

[10] Part of the content of this section was published at: *Muñoz, J. E., Cameirão, M. S., Rubio, E., Paulino, T., & i Badia, S. B. (2016). Modulation of Physiological Responses and Activity Levels During Exergame Experiences. In 2016 18th International Conference on Virtual Worlds and Games for Serious Applications. IEEE*

Before thinking on a real-time adaptive system, we decided to study the physiological differences of playing the same customized videogame (Pong) with and without (Control) involving physical exercise. Particularly, we wanted to know if through a controlled modulation of game parameters, we would be able to elicit the desired physiological responses. We used body-based metrics and game data to address the following research questions:

i) Is game performance better during Exergaming or Control?
ii) Is electrodermal activity modulated by game interface or events and difficulties?
iii) Are cardiovascular and exercise levels modulated by game interface, difficulty and game events?
iv) Is user's movement intensity affected by game difficulty during Exergaming?

6.1.1 Methods

Exergame and system setup

Exergame Design: the used Exergame, called Exerpong, is an adaptation of the classic 2D Pong in which the player controls a virtual paddle to bounce a ball. Two different interaction modes are available: *Exergaming* and *Control* (with a conventional joystick). Exerpong was developed using the Unity 3D game engine (Unity Technologies, San Francisco, USA). The RehabNet Control Panel (Reh@Panel) software [152] is used to interface a depth sensor with Unity 3D. Through calibration, the user's waist position is mapped to control a virtual paddle. Three different difficulty levels were implemented (easy, medium and hard) based on the modification of the velocity of the ball, size of the ball, and the size of the paddle. No scores were provided to avoid influencing the long-term perception of success or failure. Game events were unequivocally labeled as missed balls or ball interceptions. Audiovisual stimuli (red and green visual feedback, and positive and failure sounds) were used during gameplay to provide feedback on performance.

Experimental Setup: a white PVC surface (2.5 m x 3.0 m) was used to project the Exerpong game on the floor in front of the participants (*Figure 23*). The projection had a resolution of 1280x720 pixels, and the perspective was corrected to the surface using a mapping application. We used the fighting stick EX2 for Xbox360 to enable the control of the virtual paddle with a joystick in the *Control* condition. Users sat in a chair in front of the floor perpendicular to the paddle-movement axis and controlled the joystick using their right hand. A Kinect v1 sensor (Microsoft, Microsoft, Washington, USA) enabled the control of the virtual paddle through body motion in the Exergaming condition. EDA and ECG signals were recorded through a Bluetooth connection using the BioSignal Plux toolkit (Plux Wireless Biosignals, Lisboa, Portugal), a wearable body-sensing platform. EDA signal was recorded using two Ag/AgCl electrodes attached to the middle phalanges of the middle and index fingers of the participant's left hand. ECG signals were recorded using a surface mount triode dry electrode with standard 2 cm spacing of silver chloride electrodes placed on the V_2

pre-cordial derivation. Conductive gel to facilitate signal recording was used in some participants when necessary.

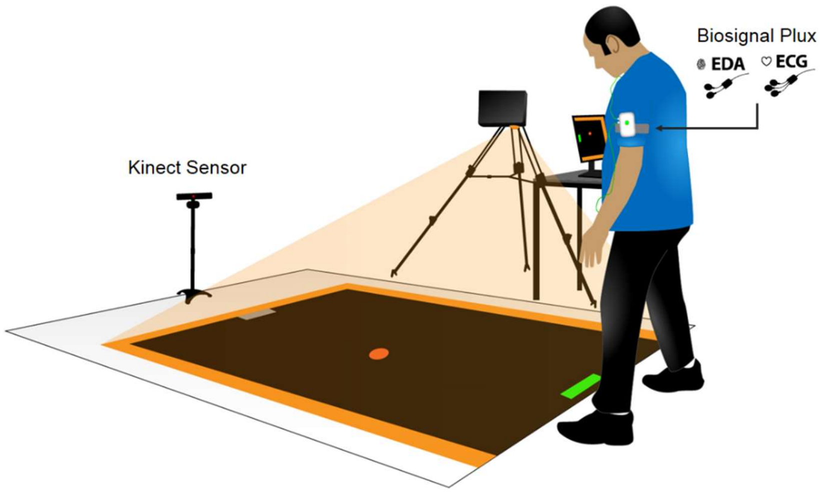


Figure 23. Diagram depicting the Exerpong setup consisting of a Kinect sensor, a projected environment and a wearable physiological kit. The user stands in front of the projection and controls a virtual paddle.

Participants

Seventeen community-dwelling older adults (14 women, 3 men, ages M=64.5 years, SD=6.4 years, height M=1.57 m, SD=0.67 m, mass M=69.1 Kg, SD=12.2 Kg.) were recruited at a local senior sports facility. Senior fitness tests scores in balance-8 Foot Up and Go (M=4.6, SD=0.6), cardiorespiratory - 2 minutes Step Test (M=97, SD=18) and musculoskeletal - 30-second Chair Stand Test (M=18, SD=2) were used to characterize the functional fitness level of users. All participants were right-handed, had no recent upper/lower limb injuries, were able to stand up without any help and had no neurological disorders that prevented the understanding of the experiment. 58.8% of the participants had no past experience with computer games. All participants gave their informed consent before participation (Appendix D).

Outcome measures

EDA signal processing and feature extraction: to eliminate high-frequency noise, an 8th order low-pass filter with a cut-off frequency of 15 Hz was applied. To filter spurious spikes produced by physical movements we used a 5th order median filter. EDA data from different users were normalized as a percentage of their minimum and maximum values to allow for comparison. Phasic EDA responses (GSRs) were assumed to begin between 1 and 4 seconds following stimulus onset [181]. GSRs were extracted synchronously with the Exerpong game events to study their relationship (*Figure 24*). An event specific GSR index was computed as follows:

$$GSR_{index}\,(x) = \frac{GSR_x}{GSRs} * 100\% \qquad (2)$$

Where *x* can be either *BI (ball interceptions)* or *MB* (*missed balls)* events and the index computes the % of *x* specific GSRs out of the total of GSRs detected. This percentage quantifies the responsiveness of each user to each type of game events.

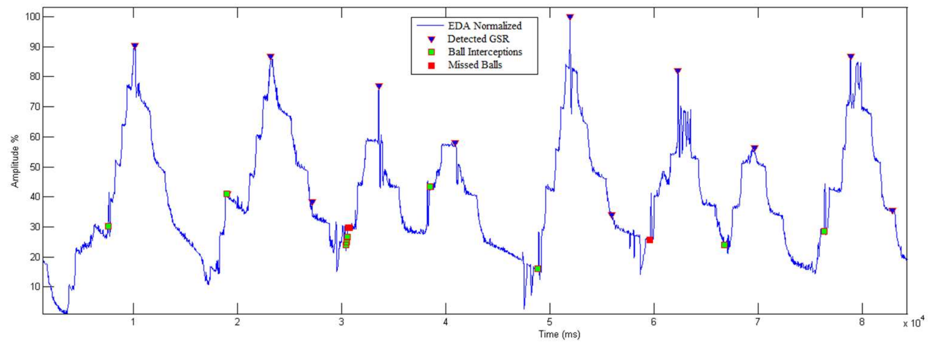


Figure 24. Example EDA signal processing of one participant. GSRs are detected and matched with ball interceptions and missed balls.

ECG signal processing and feature extraction: baseline wandering, an amplitude shifting phenomena due to gross movements but also to tiny movements such as respiration [134], were filtered. Some EMG noise in the ECG signal was unavoidable and could not be filtered. Results of R-peak detection were manually reviewed and corrected when necessary to obtain the RRI time series and HR data. Temporal HRV parameters such as the SDNN and RMSSD were computed. In addition, HR_{max}, VO_{2max} and EE (METs) were used as CRF biomarkers (all of them derived from HR data).

Kinematic signal processing and feature extraction: given 3D user tracking information from the Kinect sensor, we computed the kinetic energy (KE) of each joint as the norm of their velocity vector. The body kinetic energy was approximated as the weighted sum of each joints' KE, as follows:

$$KE(f) = \frac{1}{2}\sum_{i=1}^{n} m_i v_i^2 \qquad (2)$$

where m_i indicates the mass of the i-th joint. We used a mathematical approximation assuming a uniform distribution of each tracked joint, that is m_i was the self-reported mass of each individual divided for the number of joints (17 using Kinect V1).

Questionnaires: the Subjective Units of Distress Scale (SUDS) was used as a subjective measure of the level of distress, fear, anxiety or discomfort on a scale of 0-10. The usability of Exerpong in the two interaction modes was assessed with the System Usability Scale (SUS) [182]. SUS provides a quantification of usability through information on users' interaction.

Experimental Protocol

Participants were invited to play Exerpong in its two configurations, *Exergaming* and *Control*, in the same session and day *(Figure 25).* Each game block (easy, medium, and hard) was programmed to increment the difficulty every 30 seconds. Each game block lasted for 3 minutes. Before the start of the experiment, participants were instructed on the use of the different interaction modes. Participants were required to keep silence during gameplay and be seated and calm for 5 minutes between conditions to allow physiological signals to return to a resting state. The order of conditions was randomized such that half of the participants started with the *Control* condition and half with the *Exergaming* one. Each condition lasted approximately 30 minutes (including setup, instructions, resting, gameplay, and questionnaires). The SUDS scale was projected on the floor and answers automatically collected after each game block during the resting periods. The SUS was gathered through semi-structured interviews after each experimental condition.

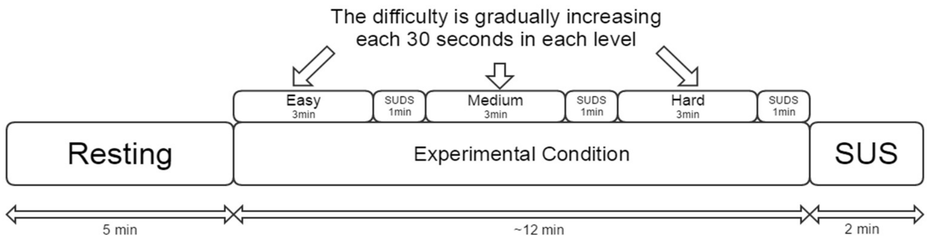


Figure 25. Experimental Procedure. The procedure is the same for both experimental conditions (*Exergaming* and *Control*). The SUDS: Subjective Units of Distress Scale, SUS: System Usability Scale

Data processing and Analysis

Physiological and kinematic information was recorded synchronously with Exerpong data. Exerpong data and events were stored at a sampling frequency of 30 Hz for post-processing. Physiological data were acquired at a 1000 Hz sampling rate, and the kinematic data was captured using the Kinect v1 provided spatial coordinates (X-horizontal, Y-vertical, and Z-depth) of 17 body points. Data were stored in CSV files and processed using Matlab v2012a. The PhysioLab toolbox was used to process both EDA and ECG signals [108]. EDA data sets of four participants were discarded due to high noise, non-removable artifacts, and data corruption.

The two principal components of a Principal Components Analysis (PCA) were used to identify colinearities and redundancy in the parameters extracted from EDA and ECG signals. Two parameters were selected from EDA [GSR_{Index}(*BI*) and GSR_{Index}(*MB*)] and three parameters from ECG (HR, SDNN, and METs). The normality of all distributions was assessed using a Kolmogorov-Smirnov test. When data were non-normal, non-parametric tests were used. A two-way repeated measures ANOVA was used to compare experimental conditions and difficulties. Differences between difficulty levels were assessed by evaluating contrasts. Main and interaction effects were also explored. For kinematic and game performance data, a non-parametric analysis using Friedman test was used to assess the effect across conditions. Furthermore, a Wilcoxon signed-rank test was used for pairwise comparisons for the main effect of difficulty. All statistical tests were performed using SPSS (21.0, IBM Corp, Armonk, NY) and the significance level was set to 5% ($p < 0.05$). The PCA analysis was carried out in Matlab.

6.1.2 Results

Is game performance better during Exergaming or Control?

Game performance was defined considering the number of ball interceptions and missed balls. Participants showed higher performance in the *Exergaming* condition (ball interception, M=61.8, SD=5.69, missed balls, M=55.0, SD=6.4) as compared to the *Control* condition (ball interception, M=52.1, SD=5.1, missed balls M=59.8, SD=6.6). A Friedman test revealed that there was a significant difference in game performance depending on which condition was used, $\chi2(1) = 12.75$, $p < 0.05$. User's performance decreased considerably in the hard difficulty level by increasing the number of missed balls in the two conditions. A Wilcoxon test revealed significant performance differences for easy-to-medium and easy-to-hard difficulties, $T = 124$, $p < 0.05$, $r = -2.25$, $T = 119$, $r = -2.01$, respectively.

Is electrodermal activity modulated by game interface or events and difficulties?

GSR_Indexes for ball interceptions and missed balls, for the two conditions and three difficulty levels, were computed. There was a significant main effect of condition for the $GSR_{Index}(BI)$, $F(1.0, 12.0) = 8.84$, , $p < 0.05$. Users were more responsive to ball interceptions during *Exergaming* than during conventional interaction for easy (*Control*: M=36.6, SD=22.0, *Exergaming*: M=44.6, SD=27.9) and medium (*Control*: M=34.5, SD=17.7, *Exergaming*: M=56.4, SD=18.4) difficulties. No significant differences for game difficulty were found for $GSR_{Index}(BI)$. Instead, $GSR_{Index}(MB)$ differed across the main effect of the type difficulty, $F(2.0, 24.0) = 60.0$, $p < 0.05$, but not for the main effect of condition. Pairwise comparisons identified significant differences among all difficulty level comparisons: easy-medium, medium-hard, and easy-hard.

Are cardiovascular and exercise levels modulated by game interface, difficulty and game events?

HR response to the game, computed as the average HR during the experimental condition minus HR_{rest}, for *Control* and *Exergaming* and difficulty levels are shown in *Figure 26*. A higher HR during Exergaming condition and a modulation with the difficulty level was identified. There was a significant main effect of the type of condition on participant's HR, $F(1.0, 16.0) = 92.7$, $p < 0.05$.

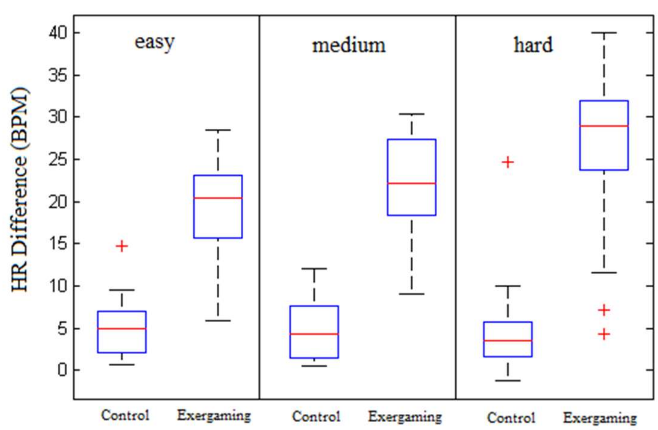


Figure 26. Boxplot of HR responses ($HR - HR_{rest}$) by difficulty and condition.

The interaction effect between the type of condition and the type of difficulty used, $F(1.0, 16.0) = 5.69$ was also significant indicating that the condition had different effects on user's HRs depending on the difficulty. Furthermore, a post hoc test using Bonferroni correction revealed that HR values for easy compared with medium difficulty levels were significantly different, $F(1.0, 16.0) = 5.6$. The remaining comparisons revealed no significant differences. Analysis of HRV revealed a significant main effect of the type of condition used for the intervention on the user's SDNN values, $F(1.0, 16.0) = 5.9$, $p < 0.05$. SDNN values for Exergaming (M=84.1, SD=56.1) were higher compared to Control (M=52.7, SD=44.9). There was no significant effect of the difficulty level over the SDNN values for the experiment.

Data showed that the METs during Exergaming were significantly affected by the difficulty level, $F(1.25, 1.0) = 5.09$, $p < 0.05$, although pairwise comparisons indicated no significant differences between difficulty levels: easy (M=6.05, SD=1.34), medium (M=6.38, SD=1.36), and hard (M=6.98, SD=1.99). The computed METs reveal that the Exergaming condition induces moderate physical activity levels (5.0 <METs<6.99 [6]) regardless of its difficulty level (*Figure 27*).

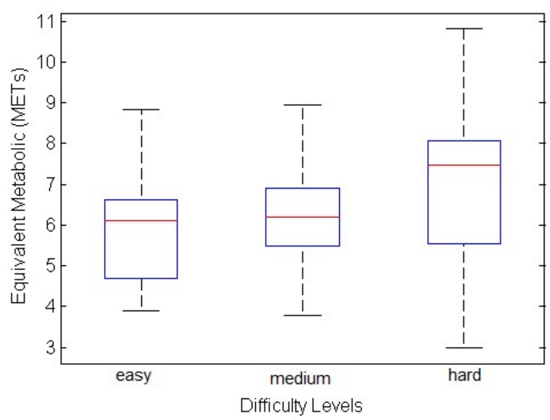


Figure 27. Metabolic Equivalents (MET) exerted during Exergaming for easy, medium and hard difficulties.

Is user's movement intensity affected by game difficulty during Exergaming?

The influence of game difficulty over movement intensity, measured as the KE, during the Exergame condition is shown in Figure 28. A Friedman test revealed that the difficulty level had a significant influence over KE, $\chi2(2) = 12.87$, $p < 0.05$. KE values were: M=1361, SD=959 in easy, M=1866, SD=1045 in medium and M=2766, SD=1381 in hard. A Wilcoxon test revealed significant pairwise differences in KE for easy-to-hard and medium-to-hard difficulties $T = 118$, $r = -2.5$, $T = 128$, $r = -3.1$, respectively.

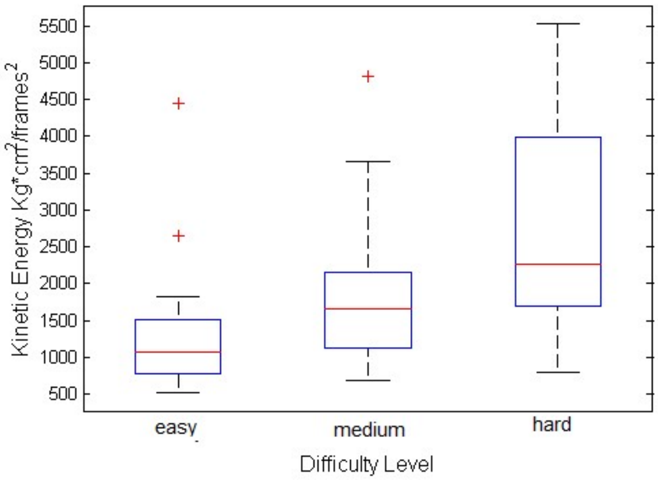


Figure 28. Boxplot of Kinetic energy for each difficulty level during Exergaming condition.

Usability and Game Experience

The usability of the videogame was rated as good (defined as SUS > 71.4 [183]) in both Control (M=78.2, SD=14.7) and Exergaming (M=84.7, SD=14,7). A Wilcoxon signed-rank test showed that the 5-point difference in favor of Exergaming was not significant. Subjects' ratings on distress as assessed by the SUDS was low for both Control (M=2.38, SD=2.24) and Exergaming (M=2.33, SD = 2.34), and not significantly different. However, a Friedman test revealed that the difficulty level had a significant effect on the SUDS score: Control: $\chi^2(2) = 15.5$, $p < 0.05$ and Exergaming $\chi^2(2) = 19.8$, $p < 0.05$.

6.2 Closing the Loop: Biocybernetic Implementation Pilot Study[11]

Previously, we showed how the customizable Exerpong modulated the cardiovascular responses in active older adults by manually changing the game difficulty [51]. In this section, our primary motivation was to create an intelligent adaptation layer for exergames which can enhance their health benefits via physiological sensing, that means closing the BL. Thus, here we evaluated the impact of biocybernetic adaptation in an exergame intervention with active senior adults to assess the effectiveness of physiologically modulated systems in accomplishing CRF recommendations. We aimed to quantify the cardiovascular physiological responses of users during a 20 minutes session as well as the game user experience. We compared this adaptive approach to the conventional exercise routine of a senior gymnasium with fifteen community-dwellers. Our approach uses HR data recorded from a commercial-grade smartwatch, and the exergame online adaptation is made based on game performance and the targeted HR levels. The main goal is to validate our physiologically adaptive version of the Exerpong as an effective cardiorespiratory training tool for the senior population, following the ACSM guidelines. Meeting the recommendations

[11] Part of the content of this section will be published at: *Muñoz, J. E., Cameirão, M. S., Rubio, E., & i Badia, S. B. "Closing the Loop in Exergaming - Health Benefits of Biocybernetic Adaptation in Senior Adults", Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play. ACM, 2018.*

is particularly important in the older population since this can maximize the benefits of cardiovascular exercise while keeping the users in a safe zone avoiding risks of over exercising [35]. We address the three following research questions:

i) Is our physiologically adaptive exergame more effective than a conventional fitness routine?
ii) Is the biocybernetic adaptation complying with health recommendations for the older population?
iii) How is the exergaming experience perceived in terms of playfulness and self-reported efficacy?

6.2.1 Methods

Exergame and System Setup
Exergame: Inspired in the breakout game and with the idea to make the Exerpong more stimulating regarding gameplay, we added a layer of virtual and colorful bricks in such a way that when a brick is hit twice, it is destroyed. After destroying all the bricks on screen, a different brick distribution is presented. It is worth clarifying that bricks have no physical influence in the ball's trajectory. Players score via destroying individual bricks as well as when clearing all brick in a level. Audiovisual stimuli are presented once the ball is hit with the paddle, displaying sparkling particles and a thumbs-up icon, and reproducing a reinforcing sound. In the same way, a punishing sound and a red screen are used every time a ball is missed, reflecting low game performance. The game allows the physical training of balance, flexibility and lower limbs strength while the physiological adaptation is oriented to maximize the cardiorespiratory performance.

Setup: The setup used here is very similar to the one described in the previous experiment (*Figure 29*).

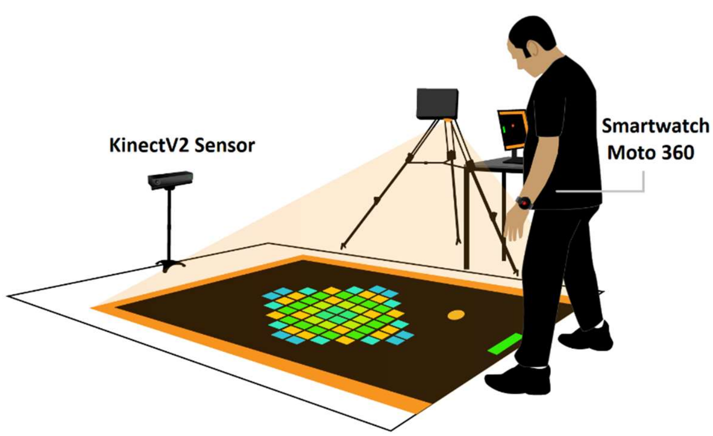


Figure 29. Diagram depicting the experiment setup for Exerpong that uses a KinectV2 sensor, the projected game in the floor and a smartwatch for HR recordings.

For players' position tracking, we used the KinectV2 sensor (Microsoft, Washington, USA), which sensed the player's waist position and mapped it to the paddle position. For the HR data, we used a Motorola 360 smartwatch synchronized with a cellphone. The smartwatch used a photoplethysmography (PPG) sensor to record and stream the heartbeats using the PhysioVR framework [153], which sent the data at 1Hz directly to a signal acquisition panel on a host computer. When compared with the gold standard (ECG), it has been shown that PPG sensors possess a very high accuracy for measuring HR even in complex conditions such as exercising [184]. The connection between the smartwatch and the exergame was made using UDP communication through the BL Engine (see section 3.3) [147].

Adaptive Rules: the ultimate goal of the biocybernetic game adaptation is to drive players to reach their target HR zone following the CRF guidelines for seniors. For the target HR, we used 55% of the HRR which is in the midst of the ACSM guidelines (40% - 70%) for older adults [99]. Considering that and following the dual flow model for exergaming [156], the Exerpong adaptations were developed for *Gameplay* and *Cardiorespiratory Fitness* as follows:

- For the *Gameplay* adaptation, two adaptive rules were used to improve the game attractiveness and balance the challenge: i) the paddle size increases once the player misses a ball and decreases once he/she hits it, and ii) the ball velocity automatically decreases if the player misses three consecutive balls.
- For the *Cardiorespiratory Fitness* adaptation, we implemented a proportional controller ($\mathrm{P_c}$) using the real-time HR data. The ball velocity increases if the 30 seconds HR average ($\mathrm{HR_{30sec}}$) is under the target HR and decreases it otherwise. K_p is the proportional constant used for sythe stem’s triggering ($K_p = 0.06$ in this experience). The proportional control followed equation 3:

$$\mathrm{P_c}{=}\mathrm{K_p}(\mathrm{targetHR}\text{-}\mathrm{HR_{30\,sec}}) \qquad (3)$$

Participants

We recruited fifteen community-dwelling older adults (11 females, ages M = 66, SD = 7 years, height M = 1.60, SD = 0.08 meters, weight M = 73.7, SD = 14.8 Kg) from a local senior gymnasium. The characteristics and fitness parameters of the recruited users are described in *Table 10*. As inclusion criteria, we used the 6-min walk test from the senior fitness test battery [146] and identified users in the 45th to the 60th percentiles (*Table 10*). The 6-min walk test score measures the distance (in meters) walked over 6 minutes. We also required users without cardiac-associated diseases (self-reported) and cognitive skills sufficient to understand the activities. The short form of the International Physical Activity Questionnaire (IPAQ-SF) was used to screen the health-related physical activity behaviors of the population, illustrating that four participants were physically active and ten were minimally-active. Only one user fell into the inactive category. Twelve reported never having played videogames before, while three reported playing videogames a few hours per week as a leisure activity. Two users reported being medicated for high levels of blood pressure and two reported past heart-issues.

Table 10. Fitness parameters describing health status and endurance characteristics of participants. BMI: body mass index, VO2max: maximum oxygen uptake, BPM: beats per minute.

Characteristic	Mean Values ± SD
BMI (kg/m^2)	28.9 ± 5.2
Resting HR (BPM)	72.9 ± 12.9
Maximum HR (BPM)	161.7 ± 4.7
VO_{2max} (unit)	2.3 ± 0.4
6-min walk test (m)	540.7 ± 31.9

Users volunteered following a detailed explanation of the experiment and after having first contact with the system that was already installed at the senior gym. The only compensation offered by the research team was a post-gaming explanation of the HR data after the experiment. Participants signed an inform consent for participating in the study (Appendix D).

Outcome Measures

Heart Rate and Effectiveness Metrics

HR data from the smartwatch was used for the comparative analysis. Effectiveness metrics encompass the root mean square error (RMSE) between the HR and the target HR and the time in the target zone ($T_{in\text{-}target}$), which expresses the total duration that people spend in the expected fitness zone (40% - 70% HRR).

Fitness and Kinematic Metrics

The maximum oxygen uptake (VO_{2max}) which describes the functional capacity of the cardiorespiratory systems was computed using the ratio between the HR_{max} and the HR during a resting state [185]. The HR_{max} was computed using Tanaka's formula [138], an age-dependent model to compute the maximum stress level of the cardiac muscle. Energy Expenditure (EE in $KJ*min^{-1}$) was calculated using the prediction equation developed by Keytel et al. [145] and converted to Metabolic Equivalent (METs) to express the amount of energy that a participant uses in the exercise. A pictorial version of the OMNI perceived exertion scale [99] was used to assess the perception of exertion in a 0 to 10 scale (0 extremely easy, 10 extremely hard) of each exercise right after the workout.

Questionnaires

A custom-made questionnaire was designed to collect information regarding the user experience during the exergame interaction (*Table 11*). The questionnaire's responses were gathered with individual short-interviews. Eight items were evaluated using a 5-points-scale questionnaire (1- low scored, 5- high scored).

Table 11. The custom questionnaire developed for the exergame experience.

Question	Statement
Q1	How exhaustive in terms of the exercise was the experience?
Q2	To what extent do you think the exergame was fit for your fitness level?
Q3	How challenging was the experience?
Q4	To what extent are you satisfied with your performance in the game?

Q5	To what extent did you put energy in this experience?
Q6	To what extent do you think the game was responding to your tiredness levels?
Q7	How enjoyable was making exercise with this game?
Q8	To what extent will you play again this game as an exercise routine?

Experimental Protocol

Using the smartwatch and the cellphone, the HR data from each participant was recorded during a conventional workout session (*Control*) in the senior gymnasium. This training usually consists of a set of different routines that include (but not limited to): i) cardiorespiratory circuits with steps, weights and motor coordination exercises; ii) upper and lower limbs movement's routines for strength training using sticks and weights; and iii) ball exercises for balance, stability, and flexibility training. These exercise routines were focused on the functional fitness training that mainly aims at reinforcing aerobic, strength and balance abilities in the older population. An introductory training session with the Exerpong was carried out on a different day to familiarize participants with the game mechanics and the setup before doing the final intervention. This was also used as a strategy to reduce the novelty effect associated with playing exergames.

We used the collected data from the Exerpong training session to infer the proportional constant (K_p) and use it for the final control adaptive system. Right before the Exerpong training session.

Finally, on a different day, the interaction with the physiologically adaptive Exerpong (*Adaptive Exerpong*) was carried out (*Figure 30*) as follows:

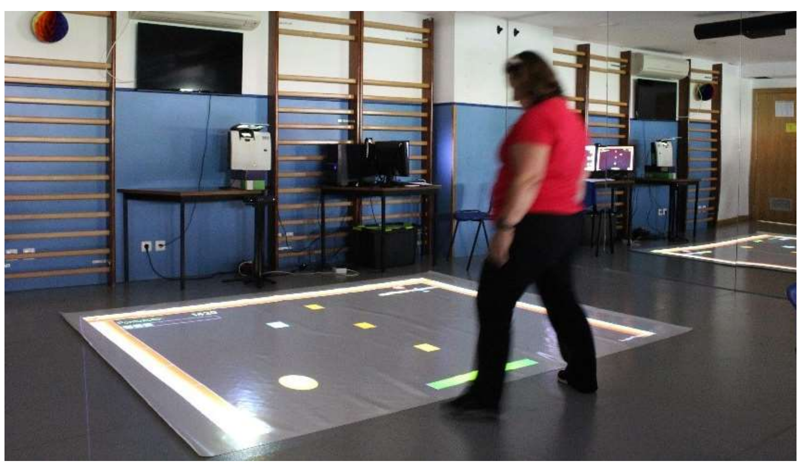


Figure 30. One of the participants interacting with the Exerpong. The equipment was installed in a local senior gymnasium.

- Participants were asked to be seated and calm for 5 minutes to record the HR_{rest}.
- A 5-minutes stretching session was performed to facilitate muscle exertion of the lower limbs.
- The age, HR_{rest} and the targeted exercise intensity (55 %) were manually introduced per participant in the adaptive system to compute the target HR.

- Participants interacted in a 20 minutes session with the adaptive Exerpong.
- Participants answered the questionnaire.

The OMNI rating was collected shortly afterward the exercise routine for both Control and the Adaptive Exerpong.

Data Processing and Analysis

The collection of data was carried out through custom log files automatically generated by Exerpong and the BL Engine, both recording data with a sampling frequency of 25 Hz approximately. For the feature extraction process of HR, fitness and kinematics parameters, we used Matlab v.2013a. The Kolmogorov-Smirnov test was used to check the normality of the distributions. A one-way repeated measures ANOVA was used to compare experimental conditions and physiological responses. Furthermore, we used the Wilcoxon signed-rank test to compare the perceived exertion through the OMNI in both conditions. All statistical tests were performed using SPSS (21.0, BPM Corp, Armonk, NY) with a significance level of 5% ($p < 0.05$).

6.2.2 Results

Results are presented around three questions proposed regarding the health benefits of exercising with the Exerpong and the perceived user experience.

Is a physiologically adaptive exergame more effective than a conventional fitness routine?

Exercise effectiveness is measured through compliance with the ACSM recommendations for light-to-moderate aerobic exercise in older adults [37], meaning exertion levels between 40 % and 70% of the HRR. This is measured considering two main variables. The first is the RMSE, the difference between the current HR and the target HR for each participant. Players showed lower RMSE values in the A*daptive Exerpong* (M=15.2, SD=8.3) when compared with the *Control* condition (M=24.3, SD=6.4). Statistical analysis revealed that the difference was significant, $F(1.0, 14.0) = 12.3$, $p < 0.05$, $r = 0.44$.

The second measurement of exercise effectiveness was the $T_{in\text{-}target}$, which was assessed as a percentage considering the 20 minutes length of each condition. Significantly higher values, $F(1.0, 14.0) = 12.3$, $p < 0.05$, $r = 0.47$ were observed for the *Adaptive Exerpong* condition (M=60.7, SD=38), compared with the *Control* condition (M=22.0, SD=22.5). The exercise effectiveness metrics for both conditions are illustrated in *Figure 31*.

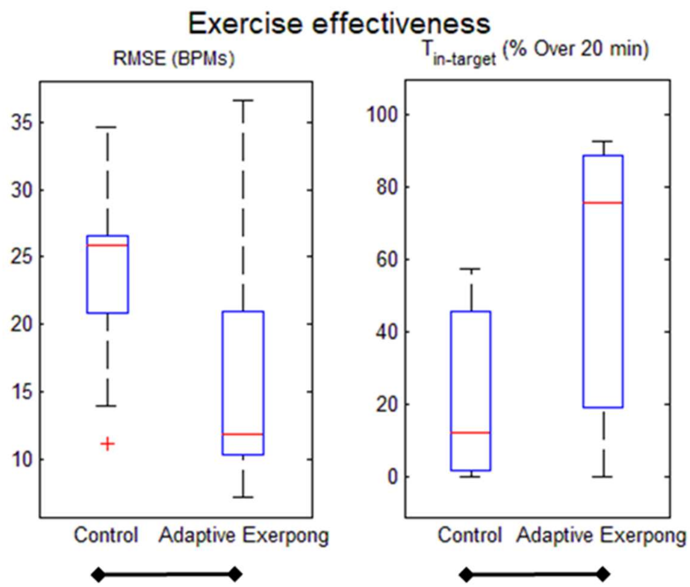


Figure 31. Boxplots of the metrics used to quantify exercise effectiveness, RMSE (left) and Tin-target (right).

Is the biocybernetic adaptation complying with the health recommendations for the older population?

We wanted to know about the exertion levels associated with each condition and inquiry into whether the exergaming experience was consistent with the healthy limits of cardiovascular training. To do that, we relied on both objective and subjective measurements. As an objective measure, we computed the metabolic expenditure. The energy expenditure in METs exhibited significantly higher values for the *Adaptive Exerpong* condition (M=8.0, SD=3.1), compared with the *Control* condition (M=6.8, SD=2.9), $F(1.0, 14.0) = 10.9$, $p < 0.05$, $r = 0.35$. Nevertheless, the computed METs showed that both the *Adaptive Exerpong* and the *Control* conditions could induce vigorous physical activity levels (> 6.0 METs), therefore complying with the recommendations for exercising during 20 minutes [99].

Lastly, subjective physical exhaustion was individually measured through the OMNI pictorial scale for each condition showing very similar levels of perceived exertion for both *Control* (M=5.7, SD=3.0) and the *Adaptive Exerpong* (M=5.1, SD=2.3) conditions. The values never exceeded the intensity of hard (score = 8) which is aligned with the ACSM guidelines for the perceived exertion [186]. OMNI differences were not significant following a Wilcoxon signed-rank test.

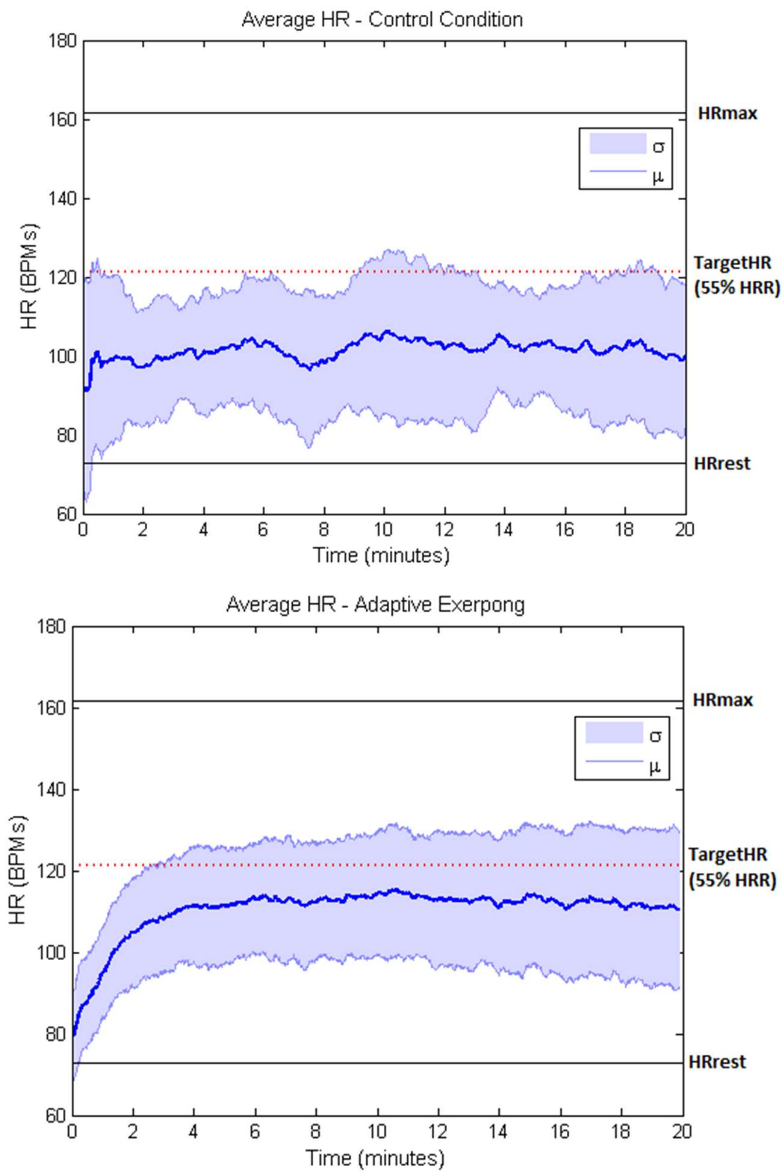


Figure 32. Average HR behavior during the Control (top) and the Adaptive Exerpong (bottom) conditions over the 20 minutes of exercise. The charts depict the mean participant profile for each condition (blue line), the ± standard deviation (blue shadow), the HR_{rest} and the HR_{max} (black lines), as well as the average target HR value used for the physiological adaptation (red dotted lines).

To aid the visualization of the HR behavior of each condition, exercise profile curves from the *Control* and the *Adaptive Exerpong* were created (*Figure 32*). The HR data from all participants were averaged over the whole session, and the curves are presented together with the standard deviation, the average values from the HR_{rest}, HR_{max}, and the target HR (55% of the HRR).

How is the exergaming experience perceived in terms of playfulness and self-reported efficacy?

We aim to understand the interaction between enjoyment, self-perception of efficacy and objective metrics of game performance and cardiorespiratory efficiency. To investigate these factors, playfulness and self-reported efficacy were measured through various dimensions following the questions in table 2, which were matched in eight dimensions (*Figure 33*) as follows: Q1- exhaustiveness, Q2- adaptability, Q3- challenge, Q4- competence, Q5- effort, Q6- responsiveness, Q7- enjoyment, and Q8- replayability. Results revealed high levels of enjoyment (4.4) and competence (4.4), reflecting a positive user experience and performance perception. The lowest scores were in the system's responsiveness (2.8) and user's exhaustiveness (3.1).

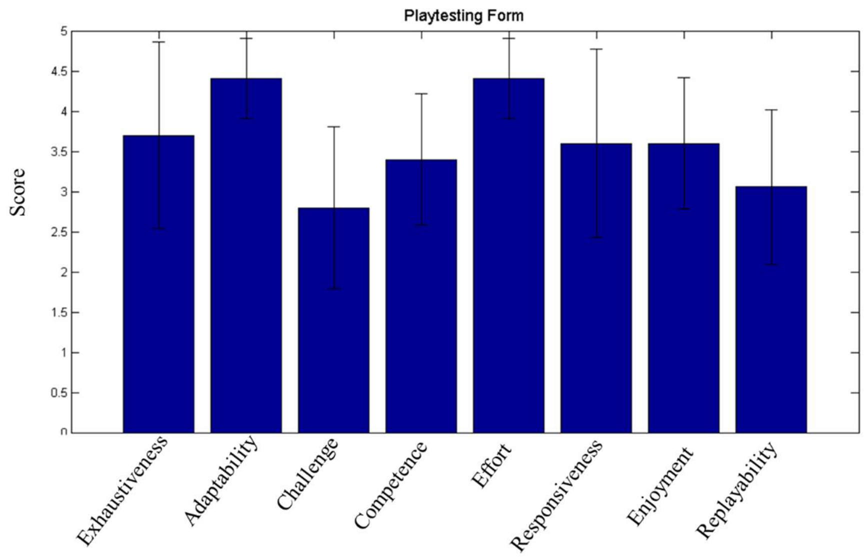


Figure 33. Results from the custom questionnaire used to investigate perceived playfulness in the Adaptive Exerpong condition.

6.3 <u>Six-weeks Controlled Study with a Cardio-Adaptive Exerpong</u>

Considering the encouraging results reported, the next step aimed at understanding the effects of physiologically adaptive Exergaming on CRF and cognitive functions in a longitudinal training (six weeks). The target population encloses a group of active older adults from a local senior gymnasium. The main objectives of this longitudinal intervention are:

- To assess the impact on the cognitive function of working-out with a physiologically adaptive Exergame during longitudinal training.
- To investigate the functional fitness, exercise effectiveness and autonomic HR regulation benefits of a longitudinal training program with a physiologically adaptive Exergame.
- To inquiry into the positive and negative affection as well as game user experience factors (such as exhaustiveness, adaptability, challenge, competence, effort, responsiveness, enjoyment and cognitive demand) of exercising through a physiologically adaptive Exergame.

This study uses an adaptation of the Exerpong to provide an interactive system for aerobic training in older adults. Although encouraging, the results of the pilot study (section 6.2) are limited and do not explain any long-term effects of training with the physiologically adaptive Exerpong. Moreover, comparing our physiologically adaptive Exerpong versus conventional training methods raised some discussions about the equivalence of the conditions and the truly effect of biocybernetic adaptation. Therefore, to extend our physiologically adaptive research approach, this study aims at investigating the effects of regular aerobic training with the Exerpong that uses a BL as adaptation strategy and compare it against a version of the same Exergame that uses a different adaptation strategy.

6.3.1 Methods

To investigate the effects of a 6-week aerobic fitness training with a physiologically adaptive Exergame on the functional fitness, cognitive, cardiovascular and game user experience in a group of active older adults, a randomized control trial experiment was designed. Two different groups (*Control* and *Cardio-adaptive*) were created, and a pre-post design was chosen to compare the main effects (see *Table 12*).

Exergame and System Setup

System Setup: the same setup described in *Figure 29* was used for this study.

Cardio-Adaptive Exerpong (*Cardio-Adaptive*): by following the dual-flow model for Exergames [156], the cardio-adaptive version of the Exerpong uses two different strategies for adapting in both attractiveness and effectiveness dimensions. Firstly, a gameplay-based adaptation (attractiveness) increases the paddle size once a ball is missed and decreases it once the player successfully hit the ball; additionally, the ball velocity automatically decreases if the player misses three consecutive balls. Secondly, the effectiveness adaptation was implemented by using a proportional controller (P_c) that increases/decreases (proportionally) the ball velocity based on the 30 seconds HR average (HR_{30sec}) and its proximity with the individual target HR (55% HRR in this case). For the HR measurements, we used the Polar H10 chest strap with a customized application that communicates with the BL Engine, which was responsible for creating the physiological adaptation [147]. The sensor records, computes and streams HR data in real-time using a sampling frequency of 1 Hz. The K_p value of the P_c controller was defined as 0.06 considering data from the previous pilot study and tests performed before the intervention started.

Performance-based Adaptive Exerpong (Control): similarly to the *Cardio-Adaptive* version of the Exerpong, the performance-based adaptation replaces the HR measurements (effectiveness adaptation) for a recursive formula that computes the player's performance based on in-game data. A performance index is computed every 30 seconds using the quantity of lost and hit balls achieved during that period of time. If the performance index is higher than a pre-defined value (performance threshold - %), the ball velocity will decrease and vice versa. The performance threshold was previously defined as 30 % (meaning that users were able to hit at least 30 % of the total balls) considering tests performed before the intervention started. It is worth noticing that the step used to increase/decrease the ball velocity is always constant in the *Control* condition, unlike the *Cardio-Adaptive* condition that uses a step proportional to the distance between the current HR and the target HR.

Participants

We invited community-dwelling older adults from a local senior gymnasium. Participants were chosen following a set of inclusion criteria that included: i) older adults in a range of age from 65 to 75 years old, ii) voluntary motivation to participate in the study (no economic reward was offered), iii) no cardiac diseases based on self-reports and historical data in the gym, iv) cognitive performance sufficient to understand the procedure, game rules and study goals as assessed by cognitive tests, and v) minimum risk of falling measured by senior fitness assessments. A detailed CONSORT flow diagram is shown in *Figure 34*.

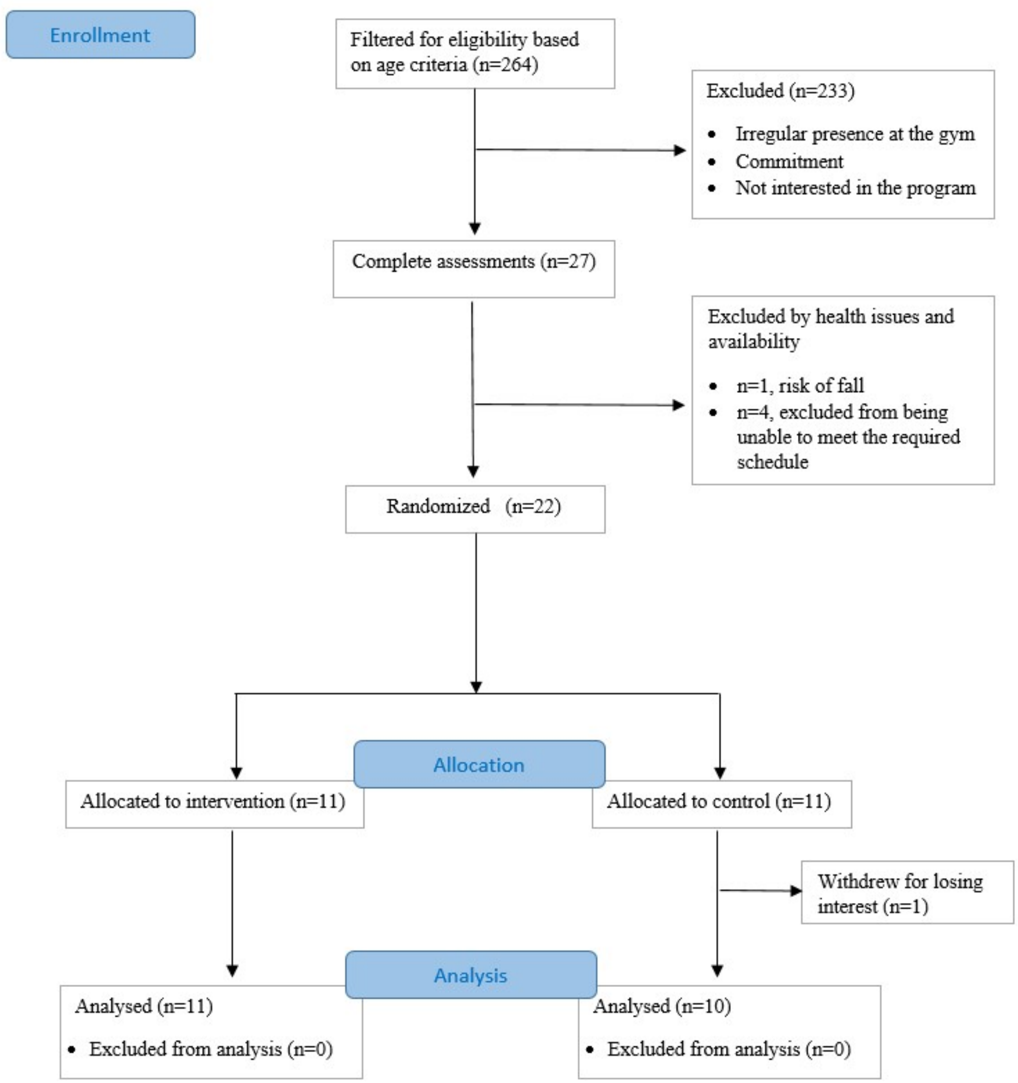


Figure 34. CONSORT flow diagram showing the phases of the study's randomization from enrolment to the analysis stage.

The interactive system was installed in a pre-located room at the senior gymnasium, which was especially conditioned regarding illumination for the Exergaming training. Posteriorly, potential participants were invited in small groups (5-10) to attend an introductory session of the experiment carried out by the researchers. The Exergame setup and mechanics were explained in detail to participants within one week, allowing the opportunity to interact with the system in a short period. The frequency, time, duration, intensity, and type of exercise were explained, and participants registered voluntarily for the subsequent assessments. Participants were carefully warned about the need of suspending their conventional fitness training in the senior gymnasium in order to participate in the study as well as having to increase their weekly-exercise time in the gymnasium by one hour (2 hours/week was the normal exercise frequency). Additionally, we used the gratuitous aspect of the assessments that we planned to carry out (cognitive, functional fitness, cardiovascular) as one of the primary motivators to enroll people in our study. Thirty-seven older adults enrolled voluntarily for the assessments and a final group of twenty-two participants (4 males, ages M=69.2, SD=2.9 years) was chosen based on the level of fall-risk and availability in the proposed schedule.

Table 12. Users' characteristics describing age, gender, heart rate resting and the scores in the Mini-Mental State Examination. Values represent mean ± SD.

Characteristic	***Control* Group (n=11)**	***Cardio-adaptive* Group (n=11)**
Age, years	68.8 ± 2.9	69.7 ± 2.8
Sex, M/F (n)	3/8	1/10
Resting HR BPMs	71.8 ± 12.6	68.9 ± 11.5
Maximum HR BPMs	159.3 ± 2.0	159.2 ± 2.0
Target HR (55% HRR) BPMs	120.0 ± 5.3	118.2 ± 6.4
MMSE	26.9 ± 2.0	26.8 ± 2.6

Outcome Measures

Cognitive Functions: one full battery and two subtests were used to evaluate multiple executive functions before and after the intervention (Pre, Post).

- The Addenbrooke’s Cognitive Examination (ACE) is a neuropsychological screening test that encompassed tests of attention, memory, fluency, language, visual perceptual, and visuospatial skills. The ACE has been extensively used to evaluate cognitive abilities as part of fitness assessment in senior adults [187]. The ACE includes the MMSE that was initially used as a preliminary cognitive screening tool (*Table 12*). We used the Portuguese adapted version provided by Firmino and colleagues [188].
- Digit Symbol Coding Subtest (Wechsler Adult Intelligence Scale – WAIS III) also called *Coding*, is a neuropsychological subtest contemplated in the processing speed index of the performance IQ branch of the WAIS test. The *Coding* subtest consists of rows of empty squares with random numbers of letters. Above them is a key pattern that pairs each number/letter with a symbol. Then, symbols must be written in the empty squares following the key pattern as quickly as possible. This subtest evaluates mainly processing and

visuomotor speed, although associative memory and sustained attention are also involved [189].

- Letter Number Sequencing (Wechsler Adult Intelligence Scale – WAIS III) also called sequencing or *Processing Speed,* is a neuropsychological subtest contemplated in the working memory index of the verbal IQ branch of the WAIS test. The *Processing Speed* subtest requires individuals to recall a series of numbers (in increasing order) or letters (alphabetical order). It evaluates aspects of the working memory, attention and mental control [189].

Functional Fitness Evaluation: the Senior Fitness Test (SFT) battery is a comprehensible and straightforward method for assessing functional fitness functions in adults ages 60 and older [146]. The SFT contemplates seven different tests covering lower (CST) and upper (ACT)) body strength, aerobic endurance (MWT6), lower (CSAR) and upper (BST) body flexibility, agility, and balance (as described before).

Heart Rate and Exercise Effectiveness: HR data during the exercise sessions was recorded using the Polar H10 (Polar Electro, Kempele, Finland) chest strap sensor. Data from the first and last sessions was used to generate the profiling HR plots (see *Figure 32*) representing the average cardiovascular behavior during the workout with both the *Control* and *Cardio-Adaptive* conditions. Additionally, the time people spent exercising between the 40 – 70 %HRR range ($T_{in\text{-}target}$) and RMSE values were also computed to quantify the cardiorespiratory effectiveness.

Heart Rate Variability: by using ECG recordings, R-to-R intervals (RRI) were obtained to carry out a heart rate variability (HRV) analysis, which helped at quantifying the autonomic cardiac regulation of the participants. ECG signals were wirelessly recorded through the Bioplux CardioBAN toolkit (Plux Wireless Biosignals, Lisboa, Portugal), a chest strap system with a sampling frequency of 1000 Hz. Pre and Post resting ECG recordings of 5 minutes were carried out in individual sessions. HR levels during resting were computed to adjust the individual targeted zones in the *Cardio-Adaptive* condition. Two groups of measurements were considered:

- Time domain HRV: the standard deviation of the RR intervals (SDNN) and the standard deviation of the root-mean-square (RMSSD) partially explained both sympathetic and parasympathetic contributions of the cardiac activity [135].
- Frequency domain HRV: the high frequency - HF (0.15 - 0.40 Hz), low frequency – LF (0.04 - 0.15 Hz) and very low frequency – VLF (0.0033 - 0.04 Hz) were extracted from the Power Spectrum Density (PSD) of the RRI signal.

Game User Experience

- Positive and Negative Affect Schedule (PANAS): this 20-item self-report tool allows evaluating the positive and negative impact of the Exergame, representing the extent to which participants experienced a pleasurable engaging exercise [190]. A 5-point Likert scale ranges from very slightly or not at all (1) to extremely (5) is used to score each emotion. Two domains can be created from the emotions reported: i) Positive affect score: interested, excited, strong, enthusiastic, proud, alert, inspired, determined, attentive, active and emotional, and ii) Negative affect score: distressed, upset, guilty, scared, hostile, irritable, ashamed, nervous, jittery, afraid.

- Custom-made playtesting feedback: from past studies, we have noticed that some senior players had problems understanding some of the standardized questionnaires, which attempted to evaluate specific domains of interest such as intrinsic motivations and perceived competence. Aiming at tackling this issue, we designed a simplistic and custom-made questionnaire that uses a 5-points-scale (1: low, 5: high) to cover eight items and complements the PANAS as follows:

    - Exhaustiveness: how exhaustive was the experience in terms of physical exercise?
    - Adaptability: to what extent do you consider the game was adapted to your physical condition?
    - Challenge: how challenging was the experience?
    - Competence: to what extent are you satisfied with your performance in this game?
    - Effort: how much effort did you involve during the exercise?
    - Responsiveness: to what extent do you think the game was responding to your tiredness levels?
    - Enjoyment: how enjoyable was making exercise with this game?
    - Cognitive demand: to what extent do you consider the game was mentally demanding?

Experimental Protocol

Participants were randomly allocated in two groups balanced regarding the cognitive (MMSE) and functional fitness assessments (CRF). Participants in one group trained with the *Cardio-Adaptive* version of the Exerpong while the other group was trained with the *Control* condition. Exercise in both groups was defined based on the ACSM guidelines [35] which can be described using the FITT (Frequency, Intensity, Time, Type) approach. Exercise frequency was defined as three times per week. This intensity was established to keep users exercising at moderate-to-vigorous physical activity levels. The time or duration of training was defined considering the guidelines for aerobic training in the older population which recommends an accumulated of 150 minutes per week [35], being divided into three different sessions of 50 minutes carried out in different days. The type of exercise used the three-stage model for aerobic exercise (warm-up, endurance conditioning, and cool-down) as shown in *Figure 35*:

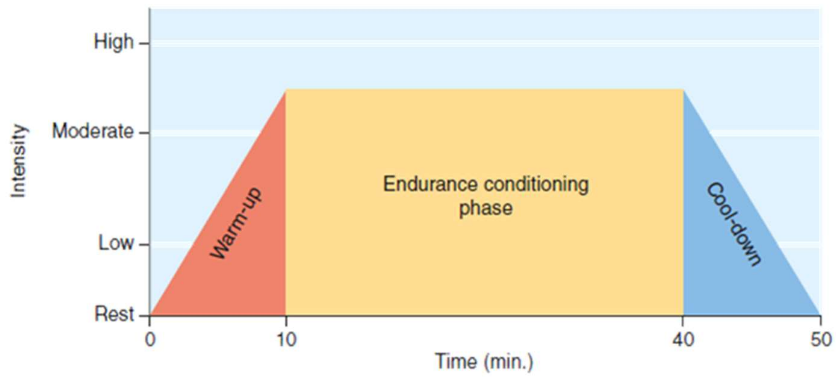


Figure 35. Overview of the recommended aerobic exercise session which includes a warming-up, endurance conditioning, and cool-down stages. Taken from *[35]*.

After identifying the potential participants of our study, we carried out the functional fitness and cognitive assessments two weeks before starting the intervention. The functional fitness tests were carried out by trained sports science professionals with experience in assessing older adults. Cognitive tests were carried out by a blind assessor in a private room, while the ACE, *Coding* and *Processing Speed* tests were evaluated in a session of about 50 minutes. ECG recordings were carried out in the morning one week before starting and one week after finishing the intervention; participants were instructed to avoid vigorous exercise on the day before data collection as well as to sleep well and report any irregularity in terms of cardiac health and medication. Five minutes recordings were taken under controlled conditions where participants were instructed to remain seated, quiet, and keeping a natural and relaxing breathing pace.

The exercise schedule was organized with the participants. Two different setups or stations of the Exerpong system were installed in a dedicated, fully equipped and conditioned room at the senior gymnasium. Each setup was configured to run the *Cardio-Adaptive,* and the *Control* conditions and individual trainers were assigned to guide the interaction with the Exergame. Participants were blind regarding the system functionalities in order to avoid any possible effect in the game user experience questionnaires. The warming up and cool-down sessions were carried out always by the same trainer. For that, regular exercises and gym tools were used (e.g., balls, elastic bands). After the third week, trainers were swopped to alleviate possible effects in regards the trainer behavior. The role of the trainers during the aerobic conditioning phase was to help seniors in being motivated and correct any possible misconduct during the workout with the Exerpong. For that, trainers used encouraging phrases as well as the Exergame dashboard to explain participants their individual post session scores. Sessions run majorly in parallel allowing the creation of a competitive environment that was beneficial to keep participants' motivation along the six weeks. Participants were also carrying a badge, which indicated their weekly schedule and the number of sessions they had accomplished and the remaining ones. In the week right after the end of the intervention, participants were evaluated with the SFTs, FAB, ACE, *Coding,* and *Processing Speed* tests while the PANAS and playtest forms were applied at the second and fifth week.

Data Processing and Analysis

HR and HRV analysis were carried out using the PhysioLab toolbox [108]. First, RRIs were computed from the ECG signals, and the best thresholds for the R-peak detection were manually and individually established for each record; artifacts were also removed using an interval correction technique. The HRV spectral analysis was performed using a Welch's Power Spectral Density (PSD) estimation with a Hamming window with signal segments of 128 samples length and segments of 64 for overlapping. The HR profiling curves were obtained after a linear interpolation process carried out complete some of the data lost during the recording process. Statistical analysis was conducted to compare the differences between the aforementioned experimental conditions as well as each condition at different moments. Categorical variables are presented in absolute values or percentages while the quantitative variables are presented through the mean value and the standard deviation. Statistical analysis was carried out through the t-student, Mann-Whitney, ANOVA or Kruskal-Wallis test for the quantitative variables. The analysis was carried out using MATLAB 2013b (MathWorksInc., Natick, MA, USA) and SPSS v16.0 (SPSS Inc., Chicago, IL, USA).

6.3.2 Results

Does *Cardio-Adaptive* Exergaming produce measurable cognitive changes after six weeks of training? If so, what are the differences with the *Control* condition?

We compared the conditions considering pre and post evaluations. In the *Control* condition users revealed significantly higher scores in the ACE total score in the post-assessment, (Mdn = 88.5), z = -2.82, $p < 0.05$, once compared with the pre-assessment, (Mdn = 86.5).

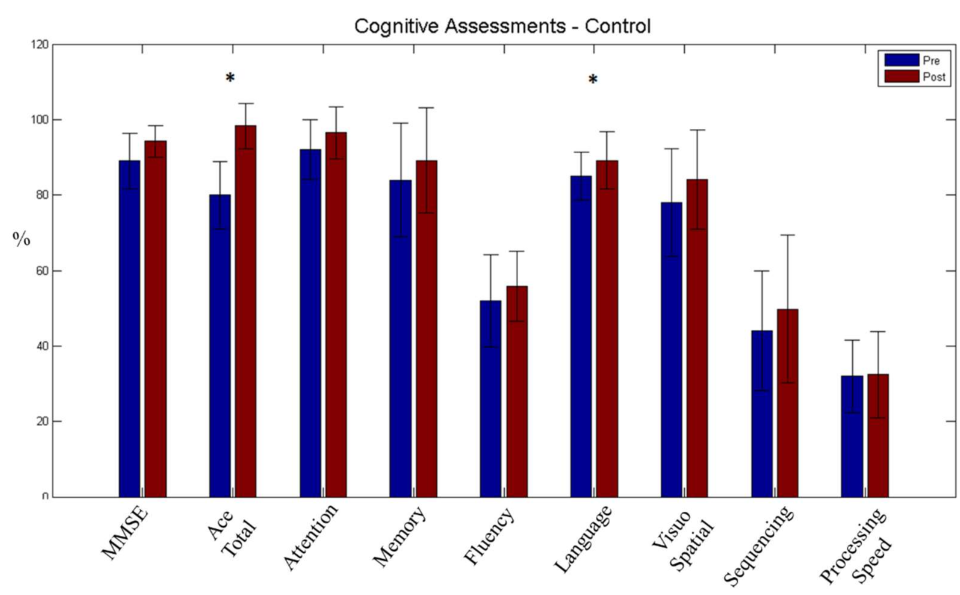


Figure 36. Differences between the Pre and Post cognitive assessments in the *Control* Condition. The ACE covered the Mini-Mental State Evaluation (MMSE), Attention, Memory, Fluency, Language and Visuo-Spatial subtests. The WAIS subtests for *Sequencing* and *Processing Speed* were also included. (*) Denotes statistical significance $p < 0.05$.

The language subtests in the post-assessment also showed significant differences (*Mdn = 94.2*), $z = -2.16$ $p < 0.05$, once compared with the pre-assessment (*Mdn* = 88.5). *Figure 36* shows a plot comparing both assessment moments (Pre and Post) for the *Control* condition. Values were normalized considering the maximum scores for each sub-tests.

Cognitive changes in the *Cardio-Adaptive* condition were similarly quantified. Results revealed significant changes in the ACE total score for the post-assessment, (*Mdn* = 86.0), $z = -2.82$, $p < 0.05$, once compared with the pre-assessment (*Mdn* = 80.0). Both, Memory, (*Mdn* = 84.6), $z = -2.36$, $p < 0.05$, and Processing Speed, (*Mdn* = 33.8), $z = -2.60$, $p < .05$, subtests were also affected in the post assessments, once compared with their correspondent pre tests (Memory: *Mdn* = 80.8, Processing Speed: *Mdn* = 27.1) as can be seen in *Figure 37*.

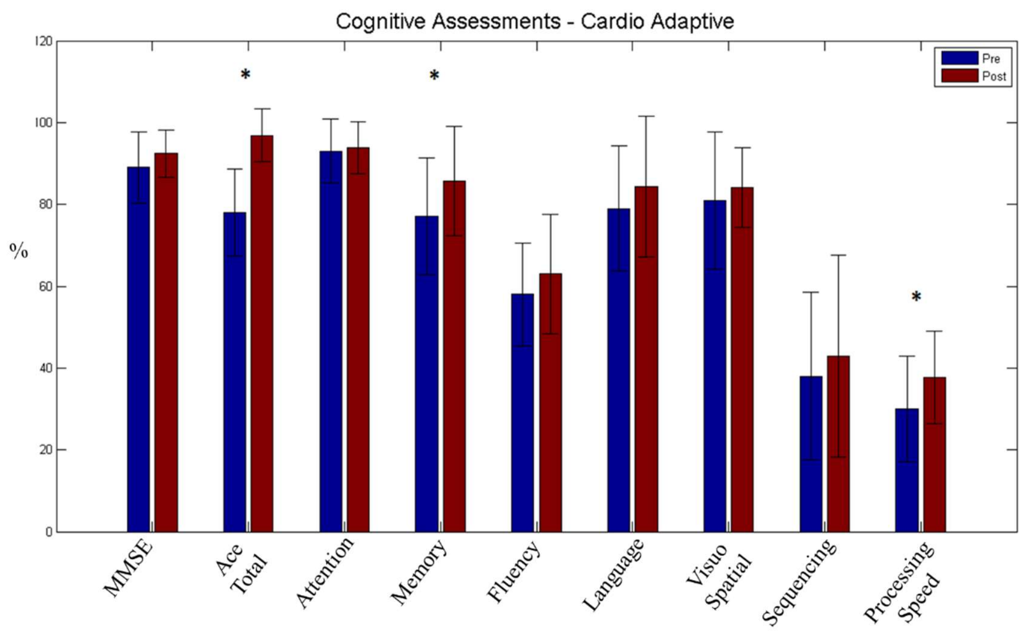


Figure 37. Differences between the Pre and Post cognitive assessments in the Cardio-Adaptive Condition. The ACE covered the Mini-Mental State Evaluation (MMSE), Attention, Memory, Fluency, Language and Visuo-Spatial subtests. The WAIS subtests for *Sequencing* and and *Processing Speed* were also included. (*) Denotes statistical significance $p < 0.05$.

What domains of functional fitness are positively impacted by means of training with the Cardio-Adaptive Exergame?

The six different subtests of the SFT battery were evaluated in the pre and post assessment moments. The *Cardio-Adaptive* condition exhibited significant improvements in the Chair Sit and Reach Test (lower body flexibility) for the post-assessment, (*Mdn* = 9.0), $z = -2.27$, $p < 0.05$, once compared with the pre-assessment moment (*Mdn* = 6.6). No significant differences were reported in the *Control* condition in regards to the functional fitness subtests.

What adaptation modality produced more effective training along the six-weeks program?

Exercise effectiveness was quantified with the $T_{in\text{-}target}$ and the RMSE values. First, the *Control* condition showed significant higher values in the time users spent in the target zone ($T_{in\text{-}target}$) for the first session, (*Mdn* = 63.86), $z = -2.49$, $p < 0.05$, once compared with the last one (*Mdn* = 37.10). Contrarily, participants in the *Cardio-Adaptive* condition spent consistently very similar times in the target zone during the first session (*Mdn* = 74.9) once compared with the last session (*Mdn* = 76.02). The Wilcoxon signed rank tests revealed non-significant differences between the $T_{in\text{-}target}$ of the first session once compared with the last one for the *Cardio-Adaptive* condition (see *Figure 38*).

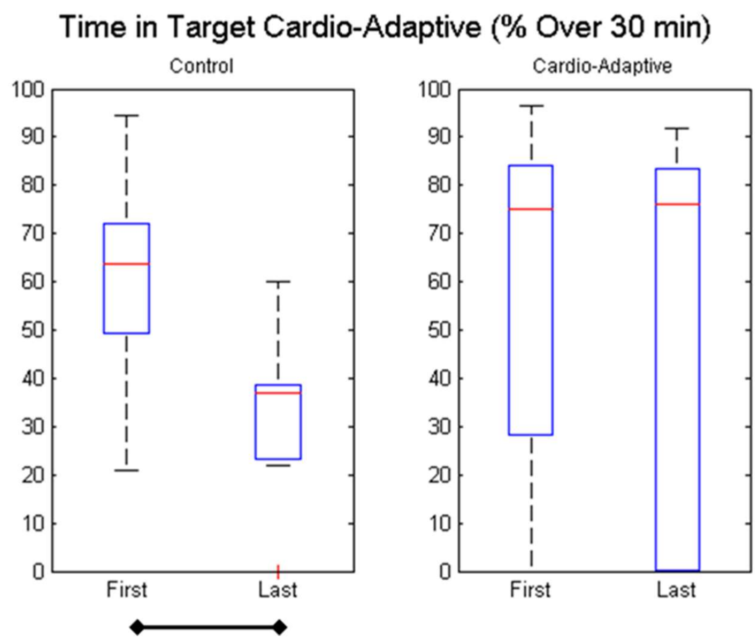


Figure 38. Boxplot showing the $T_{in\text{-}target}$ variable used to quantify the exercise effectiveness for the first and last session in the *Control* (left) and *Cardio-Adaptive* (right) conditions.

Similarly, RMSE values (in BPMs) showed significantly lower differences between the first, (*Mdn* = 14.7), $z = -2.8$, $p < 0.05$ and the last session for the *Control* condition (*Mdn* = 20.4). On the other hand, participants of the *Cardio-Adaptive* condition reported non-significantly different RMSE values between the first (*Mdn* = 14.9) and the last (*Mdn* = 15.3) session (see *Figure 39*).

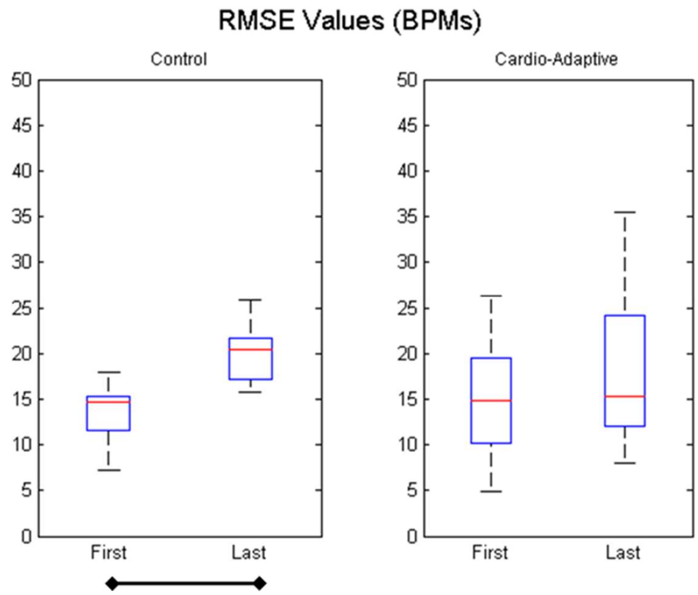
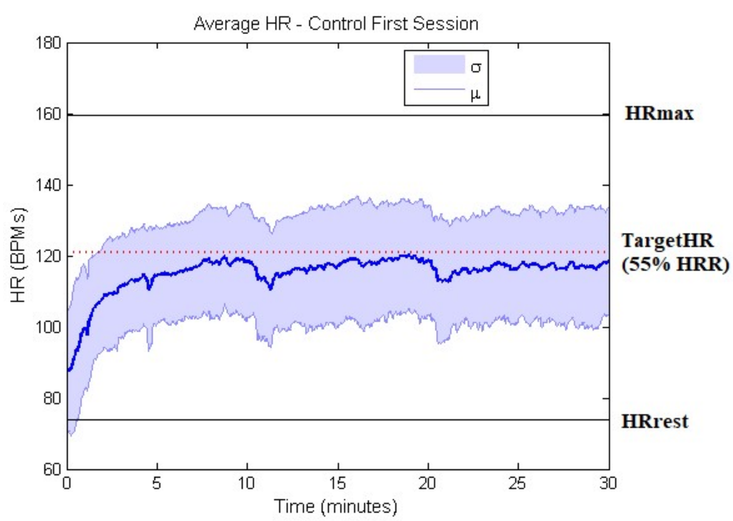


Figure 39. Boxplot showing the RMSE values used to quantify the exercise effectiveness for the first and last session in the *Control* (left) and *Cardio-Adaptive* conditions.

Finally, as we did in the pilot study, profile curves from both the *Control* and *Cardio-Adaptive* conditions were drawn to aid the understanding of the effectiveness metrics just reported. The curves are presented illustrating the mean profiles per condition with the standard deviation, HR_{rest}, and HR_{max}. During the first session, both conditions reported very similar profiles (see *Figure 40*):



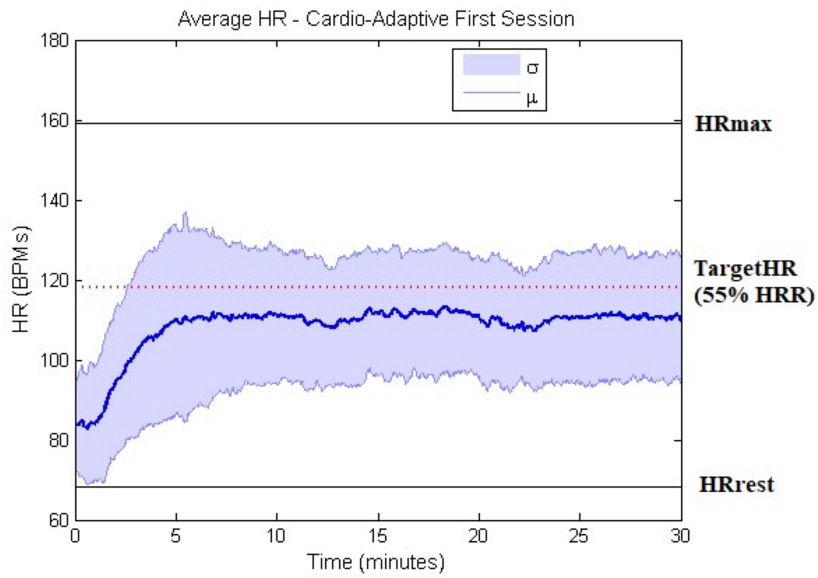
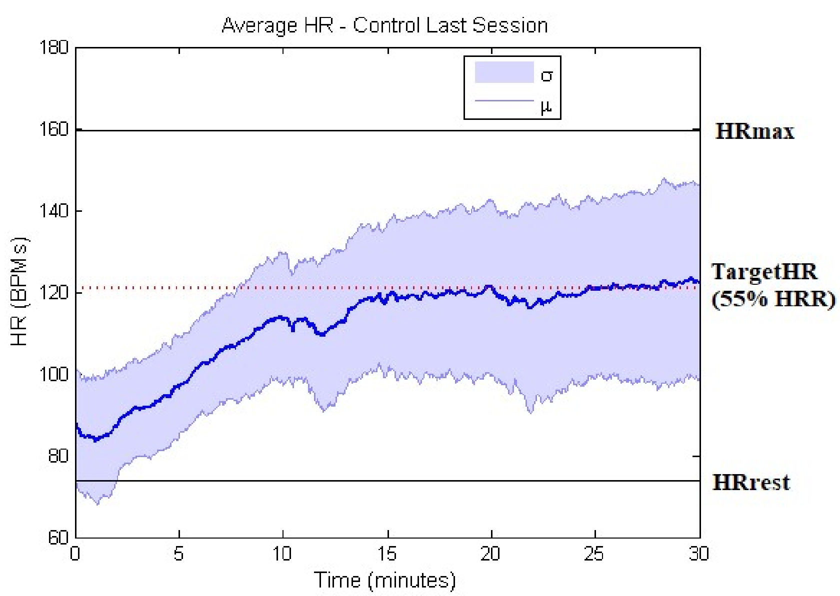


Figure 40. Average HR behavior during the *Control* (top) and the *Cardio-Adaptive* (bottom) conditions over the 30 minutes of exercise in the first session. The charts depict the mean HR participant profile for each condition (blue line), the ± standard deviation (blue shadow), the HR_{rest} and HR_{max} (black lines), as well as the average target HR value used for the physiological adaptation (red dotted lines).

However, the last session carried out in the week number six, some differences between the HR profiles of participants in the *Control* and the *Cardio-Adaptive* conditions were noticed. As shown in *Figure 41,* the data dispersion in the *Control* condition was higher than in the *Cardio-Adaptive* showing a more risky behavior towards moving participants outside to their targeted zones (top).



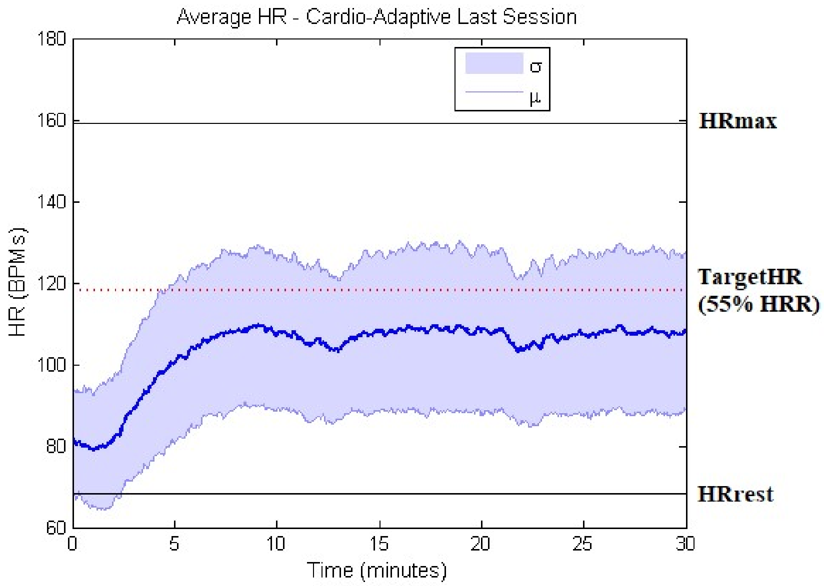


Figure 41. Average HR behavior during the *Control* (top) and the *Cardio-Adaptive* (bottom) conditions over the 30 minutes of exercise in the last session. The charts depict the mean HR participant profile for each condition (blue line), the ± standard deviation (blue shadow), the HR_{rest} and HR_{max} (black lines), as well as the average target HR value used for the physiological adaptation (red dotted lines).

What are the effects of training with adaptive Exergaming in terms of autonomic HR regulation?

Five minutes ECG recordings for Pre and Post moments were analyzed in order to extract the HRV time and frequency domain parameters. Unexpectedly, significant values were only found in the *Control* condition. First, SDNN, (*Mdn* = 26.1), $z = -2.40$, $p < 0.05$, and RMSSD, (*Mdn* = 912.7), $z = -2.80$, $p < .05$, values from the Post evaluation reflected significant increases once compared with the pre assessment moments, (SDNN: *Mdn* = 16.8, RMSSD: *Mdn* = 837.6) for the time domain branch (see *Figure 42*).

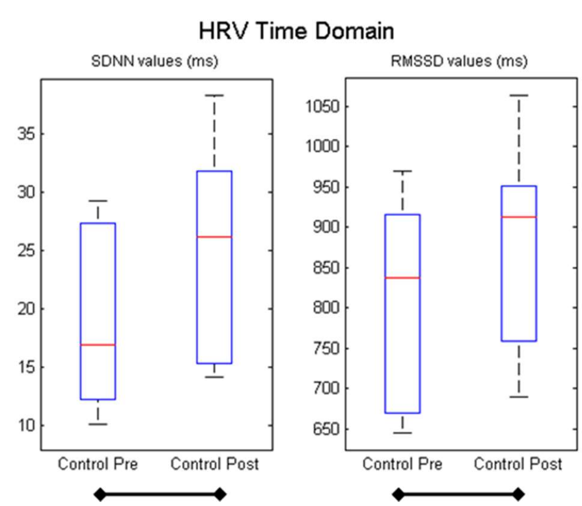


Figure 42. Time domain HRV parameters that exposed significant changes in the Control condition between the Pre and Post assessments.

Similarly, frequency domain parameters were also affected in the *Control* condition, exposing statistically significant differences in the LF, (*Mdn* = 244.8), $z = -2.40$, $p < .05$, and VLF, (*Mdn* = 3.2 $x10^5$), $z = -2.80$, $p < .05$, measured in the Post assessment, once compared with the Pre assessment data, (SDNN: *Mdn* = 196.6, RMSSD: *Mdn* = $2.7x10^5$) as seen in *Figure 43*.

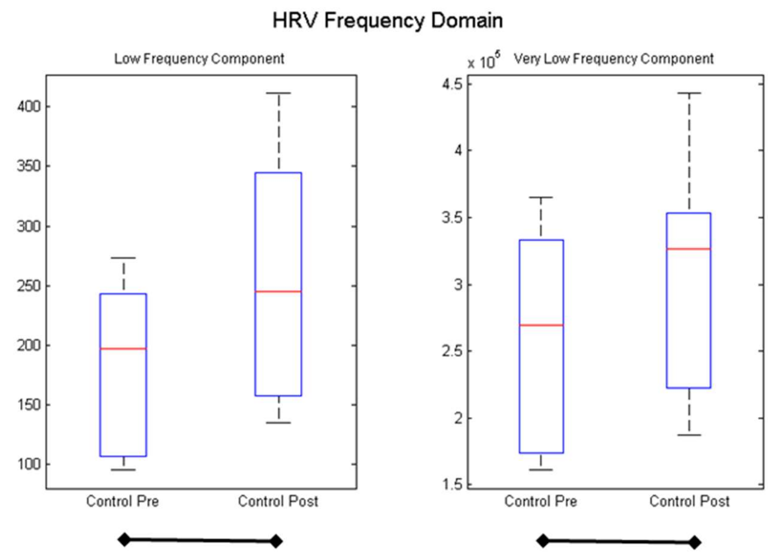


Figure 43. Frequency domain HRV parameters that exposed significant changes in the Control condition between the Pre and Post assessments.

To what extent do the different adaptation strategies affect game user experience along the six weeks training program?

Positive and negative affect were evaluated in two different moments during the intervention to evaluate the evolution of the perceived affective aspects of the intervention using the PANAS questionnaire. No significant changes were found for the *Control* or *Cardio-Adaptive* condition revealing in general, sustained levels of positive affect between the second (*Control*: Positive *Mdn* = 41.5, Negative *Mdn* = 10.5; *Cardio-Adaptive:* Positive *Mdn* = 39.0, Negative *Mdn* = 10.0) and fifth week (*Control*: Positive *Mdn* = 43.0, Negative *Mdn* = 11.5; *Cardio-Adaptive:* Positive *Mdn* = 39.0, Negative *Mdn* = 13.0). Furthermore, the custom-made playtest form revealed significant differences in both *Control* and *Cardio-Adaptive* conditions as follows: first, the perceived challenge in the *Control* condition was significantly reduced in the fifth week, (*Mdn* = 4.0), $z = -2.24$, $p < .05$, once compared with the perceived values of the first week, (*Mdn* = 5.0). Secondly, the perceived game adaptability levels were affected in the *Cardio-Adaptive* condition showing significantly lower values in the fifth week, (*Mdn* = 3.0), $z = -2.05$, $p < .05$, once compared with the perceived values of the first week, (*Mdn* = 4.0).

6.4 Conclusion and Discussion

Here, we have described the complete design, implementation, pilot and longitudinal study that demonstrates the use of biocybernetic adaptation in

Exergaming. The pathway of modeling the physiological responses, pilot prototypes, and design a randomized control trial studies seems to be a robust methodology for a meaningful integration of physiological adaptation on serious gaming. The implementation of the physiological intelligence based on HR data in the Exerpong game establishes evidence of how BLs have the potential to increase effectiveness in CRF training in older adults. The HR and HRV metrics constitutes a trustable source to quantify such effectiveness that is aligned with a well-established fitness framework [35].

First, we described an attempt to systematically study how physiological responses can be modulated through game parameters in an Exergaming experience. Exercise intensities were strongly modulated by game difficulty levels, suggesting the feasibility of the dynamic (biocybernetic) adaptation of game parameters by analyzing user's physiological responses. The game difficulty also modified HR responses, and an HRV analysis demonstrated that the interface (handheld or motion) had the most substantial influence in the modulation of beat-to-beat heart's behavior. After contrasting those findings, we noticed that we have a concise body of evidence to create a BL based on only HR levels and ball speed changes in the Exerpong. We started an iterative process trying to design adaptations that were able to persuade users to exert into the recommended targeted zones without losing the playful and enjoyment of playing the Exerpong [147]. We found our response in the dual flow model for Exergaming, which allowed us to add the recently designed BL as a physiological adaptation layer for the game. We carried out multiple iterations looking for the best way to balance both effectiveness and attractiveness [156] in the Exerpong. As we have shown, in the A*daptive Exerpong* participants exerted more than 60% of the training time in their individual target HR zone, showing in average RMSE values of 15 BPMs (difference with the desirable level). These results indicate the feasibility of using HR-based adaptation rules combined with game performance to produce effective real-time modifications aiming at fulfilling the ACSM guidelines. The pilot study demonstrated our determined effort of getting this sophisticated cybernetic technology for out-of-the-lab experiments. Our findings can be seen as one important milestone for extending its use in multiple everyday life scenarios [191]. We consider two main factors that eased the implementation of the system in the field: first, the use of smartwatches as wearable physiological sensors, which significantly reduced the complexity of wiring participants without significant expenses in accuracy [184]. Secondly, the integration of all the physiological computing components of acquisition, analysis, and translation [31] in the game engine Unity3D, helped us to create a fluid communication pathway between the BL and the exergame. Moreover, by looking at *Figure 32*, one can observe that the *Adaptive Exerpong* training exhibited a more controlled cardiac response around the target HR than the *Control.* This illustrates a desirable behavior considering safety issues and training efficacy [99].

Finally, we moved to a longitudinal intervention looking for a more sustainable and still unknown cognitive and cardiovascular benefits of a continuous exercise with an Exergaming enhanced with biocybernetic adaptation. We aligned our efforts in providing a consistent, fair and equivalent control condition for the *Cardio-Adaptive* Exerpong. We relied on a different adaptation strategy implemented in the same Exerpong that was unaware of the CRF performance of users but instead, used in-game data to compute the performance and create adaptations. Results are consistent with our initial premise that although both conditions were very similar, the biocybernetic adaptation will produce cognitive improvements in domains where the performance-based adaptation was unable. Moreover, results are similar to those previously reviewed pointing out the effects of aerobic training on cognitive skills such as processing speed in the aged population [192]. Functional fitness was also positively affected by training with the *Cardio-Adaptive* Exerpong, showing the distinctive effects of biocybernetic adaptation. Exercise effectiveness also reflected a sustained positive effect of training with the *Cardio-Adaptive* Exerpong. Both conditions reported very similar exercise effectiveness values in the first session (RMSE ~ 15 BPMs). However, only the *Cardio-Adaptive* system was able to sustain such effectiveness until the end of the training program. The HR profiling curves showed how in the last session, participants in the *Control* condition were closer to the HR_{max} once compared with participants in the *Cardio-Adaptive* condition, demonstrating how biocybernetic adaptation can stay users consistently and longitudinally in their targeted zones. Thus, physiologically enhanced Exergaming increases exercise effectiveness in cardiorespiratory training, and the effects are sustainable over time.

Moreover, technology adoption was also evaluated using game user experience metrics. Our initial assumption was to believe that 6-weeks with a frequency of three times per week might cause a deteriorated enjoyment and motivation in the final users. However, data from the questionnaires revealed that the participant's enthusiasm and positive affect was maintained throughout the study. Indeed, perceived features of the systems such as game challenge and adaptability were also affected during the study, revealing users' behavioral patterns towards a more comprehensible understanding of the Exergame and its functioning. To summarize, biocybernetic adaptation technology showed proficiency to enhance CRF performance in Exergaming for older adults, producing positive and measurable effects in cognitive and physical fitness as well as cardiovascular regulation and user experience.

7 Conclusion and Discussion

This chapter encompasses a final discussion of the most relevant aspects of this thesis document. A brief summary is organized describing the main findings and contributions for each chapter, aiming at providing a holistic view of our approach at a glance. Limitations regarding the HCI techniques, software development, and field studies are also described in detail. Finally, future directions for researching on biocybernetics and serious games for health are synthesized in a very succinct manner.

A major challenge presented in Exergaming research has always been improving adaptation and personalization. Particularly, when Exergames are used for health promotion purposes in sensitive populations such as older adults. Our research approach encompasses two different HCI techniques aiming at delivering safe, enjoyable and effective fitness training for older adults. Each technique (human-centered design and physiological computing) possesses distinctive characteristics and premises that were identified as important for enhancing Exergaming effectiveness, technology adoption and game user experience in older adults. We here demonstrated how considering essential factors such as individual physical capacities, motor or cardiovascular skills and game preferences and motivators; Exergaming training can be enhanced producing measurable and sustainable benefits for active aging. Moreover, we explored novel adaptive techniques that allow empowering Exergames with physiological awareness, thus creating an intelligent mechanism to improve CRF training. After all of this research journey, several software tools were developed to support our commitment to extend the use of physiological computing techniques in games and interactive applications.

7.1 Summary of the Main Findings and Contributions

Table 13 summarizes the tools, approaches and field studies carried out during this thesis, our main findings and contributions in the development of software tools for physiological computing, the use of human-centered approaches for Exergame design and posterior evaluation as well as the implementation of biocybernetic adaptation for enhancing CRF training.

Table 13. Summary of main findings and contributions organized by topics.

Topic	Subsections	Main Findings/Contributions
Physiological Computing Software Tools (Chapter 3)	PhysioLab	• Freely available multimodal toolbox for ECG (HRV), EMG, EDA signal post-processing • We demonstrated the software's usefulness to complement fitness assessments through ECG analysis.
	Cardiorespiratory Radar Plot	• A novel visualization tool that integrates HRV and CRF parameters in an informed radar plot. • Cardiorespiratory radar plots can be used to differentiate users' performance in functional fitness using HR data.

	Biocybernetic Loop Engine	• Freely available software tool to aid in the process of creating biocybernetic adaptation in games. • Demonstrated its use in Exergaming CRF training in two different studies.
Human-Centered Design (Chapter 4, 5)	Exergame Design	• Set of 4 fully customizable and contextually rich Exergames for multidimensional fitness training. • Guidelines for including human-centered approaches in Exergame design and research.
	Longitudinal Evaluation of Contextually-rich Exergames	• Improvements in functional fitness parameters (upper and lower limbs strength and balance) after 3-months training program. • Enhanced physical activity patterns (perceived and measured) compared to conventional training.
Biocybernetic Loop in Exergaming (Chapter 6)	Physiological Characterization of Exergaming Experiences	• Cardiovascular and arousal responses were modulated through Exergame design. • HRV analysis exposed how controlled Exergaming experiences may be used to enhance cardiac regulation.
	Closing the loop – Pilot Study	• By using Exerpong with biocybernetic adaptation, senior players exert 40 % more time in the recommended fitness levels than with a traditional approach. • Biocybernetic adaptation did not affect the game user experience (e.g., playfulness and self-reported efficacy)
	Six weeks study with a cardio-adaptive Exergame	• Important executive functions (e.g., memory and processing speed) were positively impacted by Exergaming training enhanced with biocybernetic adaptation. • The *Cardio-Adaptive* approach resulted in a safe and controlled cardiorespiratory training. • Positive aspects of training with the *Cardio-Adaptive* Exerpong (e.g. interest, excitement) were consistently scored as high along the six-weeks of training.

7.2 <u>Limitations of our approach</u>

7.2.1 Software tools limitations

Three different software tools were created as a result of our intention to integrate physiological computing technologies in Exergaming for fitness training in older adults. Although functional, the tools constitute very early and unpolished software approaches that have to be iterated in order to be able of being more extensively used. As researchers, we are used to recycling and re-using tools and scripts available, looking at speeding up our investigations. However, many technology enthusiasts that may be interested in using these technologies (e.g., clinicians, students, teachers, artists, indie developers) need more streamlined methods and user-friendly tools to accomplish their experimental goals. Thus, more hours of software optimization are needed to transform PhysioLab and the BL Engine in end-user ready and state-of-the-art tools for physiological computing.

7.2.2 Human-centered design constraints

Our contextual design approach allowed us to understand game preferences and motivators to design more personalized experiences that promote exercise in seniors. Although extensive and cohesive, the human-centered design method followed possesses four main weaknesses:

- Time-demanding procedure.
- Input from several sources (e.g., researchers, designers, health professionals) can be challenging to manage.
- Lack of a consistent, conclusive, fully reproducible, and straightforward method for contextually-rich Exergames.
- Our sample has a gender bias, which might impact the design decisions made.

Future user modeling processes for Exergame design in seniors should also innovate in the way we integrate older adults in a more proactive way, from the very early stages of game design. For instance, senior gymnasiums, game companies, and research labs might run together workshops or game jams to provoke collaborative and creative spaces for Exergame design. This will allow moving from contextual-design to a more co-creative design approach, hoping at maximizing the knowledge and participation of each subject involved.

7.2.3 Biocybernetic Adaptation; and now what?

Our cardio-adaptive approach establishes a very simplistic and straightforward method to create biocybernetic adaptation using HR data. Although effective in producing the desired levels of CRF performance, we noticed that some users were not able to reach their individual target HR levels during the pilot (section 6.2) and longitudinal study (6.3). Here, we noticed that motor skills, fragility, and balance might affect the cardiovascular performance in some users, preventing them from exerting at the recommended levels. It may be important to extend the research on this specific group of interest and investigating which adaptation strategies can be designed to achieve recommended levels. Creating effective BLs for physical training resulted in a very time-demanding and challenging task, it is a try and error process where adjusting variables and testing modulation strategies might take several iterations before getting a stable and physiologically persuasive system. Indeed, the BL Engine was a natural response for this limitation [29], allowing adaptation rules to be graphically modified in real-time, facilitating the adjustment of the BLs. Another very interesting approach would be researching in how to create real-time adaptations considering not only the pure HR data but HRV parameters as well [193], [194]. It has been shown that HRV parameters can accurately describe several human states (e.g., stress, workload) and clinical conditions (e.g., cardiovascular risks, pain), providing a very robust signal regarding information/intrusiveness for the biocybernetic adaptation [135].

Particularly, in the Exergaming scenario, an HRV-based adaptation might provide system modulations to maximize the autonomic cardiac regulation needed to produce countless health benefits [195].

7.2.4 Limitations of the Longitudinal Studies

The longitudinal studies have revealed important health benefits of exercising with both human-centered and "biocybernetically" enhanced Exergames for fitness promotion. Although the studies were carried out under rigorous research protocols, very controlled environments, and carefully designed control conditions, some limitations can be summarized as follows:

- Both studies considered a limited amount of participants, leading to well-known small sample size limitations such as variability (perceived and measured variables), bias and difficulty in extrapolating results to other populations.
- Sometimes unknown cardiac health status of participants. Mainly for the studies carried out to create and/or evaluate the biocybernetic approach, we have relied on the participants self-reports on cardiovascular condition. This may have led to an undesired variability regarding the cardiac responses (e.g., HRV analysis, HR profiles).
- Lack of blind assessments.
- Six weeks is probably the lowest amount of weeks to get measurable cardiovascular changes in older adults after aerobic training [192].
- Samples in both studies had more females.

7.3 <u>Future Directions</u>

7.3.1 Biocybernetic Loop Beyond Exergaming and Cardiovascular Signals

One of the most relevant features of the BL Engine is that it has been built with the game engine the Unity3D instead of any third-party application for physiological signal acquisition or processing (e.g., Matlab). This feature, allows the BL Engine to have a very streamlined and fluid communication with any game developed in this popular gaming platform. Videogames, interactive applications, and even novel virtual reality (VR) simulations can also integrate physiological intelligence using the BL Engine. As part of the PhD program, I had the opportunity to carry out an internship in the USA to create a target-shooting simulator for marksmanship training using VR and biocybernetic adaptation for a local company. For that, I relied on the BL Engine to create the physiological intelligence layer that will encourage people to promote self-regulation skills in order to stay calm, concentrated and collected while shooting. After the 10-weeks internship in the USA, an initial prototype of the Biocyber Physical System (BioPhyS) for military training in VR was successfully delivered showing the usefulness of the BL Engine beyond the Exergaming scenario.
Project Website: https://sites.google.com/view/johnhci/biophys

Figure 44. BioPhyS simulator developed for the J&F Alliance company under the supervision of Dr. Alan Pope from NASA Langley. Left: screenshot of the VR simulation. Right: picture of one test carried out to integrate airgun weapons.

The biocybernetic system allows the modulation of simulation variables such as the speed, size, and hardness of targets as well as variables that change the environment dynamically such as rain intensity and daylight. The modulation is made based on concentration and calmness levels from users that were found to be related with HR and HRV parameters (e.g., SDNN and RMSSD) and frontal alpha activity from the BCI device. The system provides solid evidence in the use of this technology initially developed for research purposes, but with the potential to be scaled up in many applications and industries.

7.3.2 Merging Human-Centered Design and Biocybernetic Adaptation in Exergaming

The integration of the cardio-adaptive intelligence already developed for the Exerpong might be extended for the whole set of Exergames described in this thesis. This integration will contribute to the creation of more adaptive and personalized fitness training with Exergaming. On the one hand, the Exergames created around the Portuguese traditions have shown effectiveness in producing desired physical activity metrics as well as important improvements in functional fitness. The incorporation of physiological intelligence in other fitness domains beyond the cardiorespiratory might also provide more efficient training for the older population. For instance, muscular strength training could take advantage of fatigue detection through EMG signals to adjust the training loads and its intensity to persuade people to exert in specific ranges of their maximum voluntary contraction for isometric exercise [129]. Through this strategy, each fitness dimension might be empowered with integrated biocybernetic intelligence to create adaptations on-the-fly based on real-time physiological data instead of only relying on the levels of perceived exertion.

Additionally, having more signals recorded during the workouts might significantly improve exercise prescription and fitness assessments as health professionals will have access to session-by-session physiological performance. Here, we showed how ECG data could be transformed through HR and HRV analysis into a handy tool to complement CRF assessment.

Unfortunately, the lack of specific contextual information and normative data often limits the interpretation of fitness data. We demonstrated the use of PhysioLab for CRF assessment in a realistic environment. We processed ECG signals from 17 older adults recorded during a moderate physical activity task. Firstly, our concept of cardiorespiratory radar plots was used to present fitness profiles, in comparison to standard bar chart representations, which generally hide essential information to describe the health status of the user. The cardiorespiratory radar plot approach revealed clear differences between CRF profiles by using five key HR parameters ($HR_{difference}$, HR_{max}, SDNN, EE, and VO_{2max}) and normative data for the elderly population. The granularity of our representation to characterize cardiorespiratory profiles allows a more precise and intuitive assessment of aerobic endurance using field data. Hence, the concept of cardiorespiratory radar plots can also be extended to represent other performance data of users and also over various exercise sessions.

7.3.3 Extending Physiologically Adaptive Serious Gaming to Rehabilitation

Novel approaches to virtual rehabilitation that use serious games and immersive technologies have been flourishing in the last decade. Similarly to Exergaming for exercise promotion, serious games created for rehabilitation purposes might be enhanced with novel biocybernetic technologies to maximize the clinical impact. In neurorehabilitation, for instance, passive BCI systems can deliver an automated adaptation based on the implicit information gathered during the rehabilitation sessions [196]. Workload, stress and mental fatigue states are just some of the human states that can be dynamically detected to create the physiological adaptation with the game variables. Similarly, kinematic variables can be used to create online adaptations based on the computation of parameters that describe relevant movement patterns such as coordination [130]. This biomechanical adaptation requires the use of very similar physiological intelligence to the one developed in this thesis, where desired ranges of motion can be used instead of target HR zones [197].

7.3.4 Improving the Biocybernetic Loop Engine

Although very experimental, the BL Engine has shown versatility and flexibility for being used in different gaming and simulation scenarios. However, the integration of more physiological signals and sensors (e.g., EDA) and more sophisticated adaptation techniques (e.g., machine learning) are examples of improvements that can be done to extend the BL Engine.

As it is, the software tool provides a very didactic and streamlined methodology to include physiological intelligence in games. However, more workshops and technology transfer activities should be carried out to disseminate the use of biocybernetic technologies in fields such as game design, interactive media, and bioengineering. However, it is still unclear how to move towards a final and integrated solution. More consistent technology adoption and use-case projects should be developed, showing the practical and usability advantages of such a tool.

7.3.5 Final Thoughts on Biocybernetics

Different challenges are intrinsically associated with the development of interactive systems which include the human in the loop. First, in the acquisition stage, the lack of standardization of novel physiological sensors limits the replicability of the systems to other conditions/populations as well as prevents the use of such adaptability in other applications. For the translation stage, the difficulty remains in integrating physiologically intelligent systems in daily-life activities, what encompasses several difficulties regarding sensors' portability, accuracy, and aesthetics. Furthermore, the most challenging stage, analysis, encloses both signal processing and interpretation to create in-time, coherent and helpful adaptation for augmenting human abilities. In this critical stage, inter-subject and intra-subject variability outlines a serious system design issue: while having a very sensitive and responsive physiologically adaptive tool is desirable, the extrapolation of such adaptation to other users/populations carries several limitations. Conversely, physiological systems that can be extensively utilized by several users, often fail in the level of assistance that can offer to the users and their personalization. There is not a simple solution for this dichotomy. Advancing in both inter-subject and intra-subject adaptation modes will disentangle the role of physiological and adaptive systems in the big challenge of supporting and complement human functionalities rather than replace and substitute them. Here, maybe one of the best scenarios for the exhaustive training process and complicated research setups in physiological modulation is virtual training. In the next decades, advances in virtual technologies will reach unprecedented and unimaginable advances, transforming the way in how we interact with computers. For instance, through this vivid and immersive simulation technology, one can be immersed in realistic and science fiction scenarios which will simplify learning processes via providing: a) real-time feedback of the physiological modulation by events in the virtual worlds, b) a platform with innumerable possibilities for content creation facilitating long-term technology adoption and c) a ubiquitous medium for content distribution considering the novel mobile and wearable approaches [153]. Therefore, the available opportunities offered by the current status of interactive and virtual technologies encourages the idealization of a future in where biocybernetic adaptation (of both central and peripheral nervous systems) will boost human capabilities through daily-life interactions in work scenarios as well as in leisure activities. Besides this, physiologically adaptive technologies have the potential of restoring motor and mental functionalities of people with disabilities via stimulating self-regulation skills [198]. To summarize, over the next two decades, physiologically adaptive technologies will influence the way we interact with computers allowing a more fluent communication with computer systems, augmenting user's abilities through a better understanding of our inner states and especially, it will help those with motor and mental disabilities via restructuring brain and body configurations. The key point of this transition is the training process, which I personally believe can take advantage of virtual technologies (e.g., virtual or augmented reality) and games to provide a flexible and unlimited medium for experimentation.

List of Selected Publications

Chapter 3

Muñoz, J. E., Gouveia, E. R., Cameirão, M. S., & i Badia, S. B. (2018). PhysioLab-a multivariate physiological computing toolbox for ECG, EMG and EDA signals: a case of study of cardiorespiratory fitness assessment in the elderly population. Multimedia Tools and Applications, 77(9), 11521-11546.

Contribution: the design of the PhysioLab was jointly planned with the supervisor and co-supervisors. The author developed the software toolbox in Matlab. All the authors contributed to the revision of the paper, (see: sub-section 3.1).

Muñoz, J. E., i Badia, S. B., Rubio, E., & Cameirão, M. S. (2015, August). Visualization of multivariate physiological data for cardiorespiratory fitness assessment through ECG (R-peak) analysis. In Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE (pp. 390-393). IEEE.

Contribution: the design of the data visualization technique was jointly conceived with prof. Robert Spence during a data visualization course. The author developed the technique in Matlab. All the authors contributed to the revision of the paper, (see sub-section 3.2)

Muñoz, J. E., Rubio, E., Cameirao, M., & Bermúdez, S. (2017). The Biocybernetic Loop Engine: an Integrated Tool for Creating Physiologically Adaptive Videogames. In 4th International Conference in Physiological Computing Systems. Presented at the PhyCS. (**Best Paper Award**).

Contribution: the design of the software tool was initially conceived with the supervisor. Parts of the software were jointly developed with Teresa Paulino and Luis Quintero. All the authors contributed to the revision of the paper, (see sub-section 3.3).

Chapter 4

Muñoz, J. E., Gonçalves, A., Rubio, E., Cameirao, M., & Bermúdez, S. (2018). Lessons learned from gamifying functional fitness training through human-centered design methods in Portuguese older adults. Games for Health Journal [*Accepted*].

Contribution: the human-centered design process was led by the author. Designers, developers, and games for health experts collaborated transversally along the research. All the authors contributed to the revision of the paper.

Chapter 6

Muñoz, J. E., Cameirão, M. S., Rubio, E., Paulino, T., & i Badia, S. B. (2016). Modulation of Physiological Responses and Activity Levels During Exergame Experiences. In 2016 18th International Conference on Virtual Worlds and Games for Serious Applications. IEEE. (**Best Paper Award**)

Contribution: the experimental protocol was planned jointly with the supervisors. The author carried out the experiment, data collection, and analysis. The adaptation of the Exerpong was carried out by Teresa Paulino. All the authors contributed to the revision of the paper, (see sub-section 6.1).

Muñoz, J. E., Cameirão, M. S., Rubio, E., & i Badia, S. B. (2018). Closing the Loop in Exergaming - Health Benefits of Biocybernetic Adaptation in Senior Adults. In Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play. ACM. [*Accepted*]

Contribution: the experimental protocol was planned jointly with the supervisors. The author carried out the experiment, data collection, and analysis. The integration of the Exerpong with the BL Engine was carried out by Teresa Paulino. All the authors contributed to the revision of the paper, (see: sub-section 6.2).

Summary - Curriculum Vitae

John Muñoz is a PhD student in Human-Computer Interaction at NeuroRehabLab in the Madeira Interactive Technologies Institute, Portugal. He has been studying the use of physiological signals to foster health benefits while interacting with serious games. He has designed and co-developed a dozen videogames interfaced with physiological sensors such as brain-computer interfaces (BCI), heart rate monitors, depth cams, and wearable electromyography armbands as well as a set of software tools that to promote the synergy between physiological computing and gaming.

His research interests cover:

- Physiological computing and biocybernetic adaptation
- Game user research and serious games for health
- Virtual reality (VR) applications
- Assistive technologies

Before enrolling the PhD, he got a B.S in Physics Engineering and a Master in Bioelectricity from the *Universidad Tecnológica de Pereira* in Colombia. He worked for three years as a researcher in a rehabilitation center in Colombia developing and evaluating videogames for physical rehabilitation purposes. He created the HCI Group research group in Colombia, responsible for creating an interactive rehabilitation space that used low-cost videogame technologies and human-centered designed games to promote virtual rehabilitation therapies. For this project, he was awarded in 2015 by the *MIT Technology Review* as one of the ten most innovative young in Colombia. He is a co-author of research papers that have been published on specialized journals in HCI and games for health. He has participated in conferences related to serious games and gameplay (e.g. CHI Play, VSGames) as well as physiological sensing and biomedical applications (e.g., IEEE EMBC and e-Health).

During his PhD, he conducted investigations in the fields of Human-Centered Design, and Physiological Computing applied to active aging through an adaptive Exergaming approach. As part of his PhD program, John had the opportunity of carrying out an Internship through the National Institute of Aerospace in the United States with Dr. Alan Pope, a pioneer in the field of biocybernetics. They developed a product for military training using VR and biocybernetic adaptation technologies in the J&F Alliance Company (Hampton, Virginia).

Appendices

Appendix A
Fitness Assessment Tools

- Senior Fitness Tests
- Fullerton Advanced Balance Scale
- Pictorial OMNI Rating of perceived Exertion

Concelho		Ginásio.		Ano Nasc.		Sexo	N.º de inscrição			

Número de Identificação – ID

Nome de família ______________________ **Nomes Próprios** ______________________

Morada ______________________ **Telf.** __________ **Sexo** ____

Data de Nascimento _______ / _______ / _______ **D/M/A;** **Data de Investigação** _______ / _______ / _______ **D/M/A**

Equilíbrio: Fullerton Advanced Balance Scale (FAB) (Rose et al., 2006)

1. Transpor um banco com 15cm de altura

(0) – Incapaz de colocar o apoio no banco sem perda de equilíbrio ou sem ajuda manual; (1) – Capaz de subir o banco com o membro inferior dominante, mas o outro membro contacta com o banco ou balança a perna, passando ao lado do banco, em ambas as direções; (2) – Capaz de subir o banco com o membro inferior dominante, mas o outro membro contacta com o banco ou balança a perna, passando ao lado do banco, apenas numa direção; (3) – Capaz de colocar corretamente o apoio no banco e transpor o outro apoio em ambas as direções, mas requer supervisão próxima numa ou em ambas as direções; (4) – Capaz de completar corretamente o apoio no banco e transpor o outro apoio, em ambas as direções, em segurança e sem ajuda.

2. Dar 10 passos em linha reta

(0) – Incapaz de completar os 10 passos em linha reta sem ajuda; (1) – Capaz de completar os 10 passos com mais de 5 interrupções; (2) – Capaz de completar os 10 passos, com 3 a 5 interrupções; (3) – Capaz de completar os 10 passos, com 2 ou 1 interrupções; (4) – Capaz de completar os 10 passos, sem ajuda e sem interrupções.

3. Equilíbrio Sobre um apoio

(0) – Incapaz de tentar ou necessita de ajuda para prevenir a queda; (1) – Capaz de elevar o membro inferior sem ajuda, mas incapaz de manter a posição mais de 5 segundos; (2) – Capaz de elevar o membro inferior sem ajuda, e de manter a posição mais de 5 mas menos de 12 segundos; (3) – Capaz de elevar o membro inferior sem ajuda, e de manter a posição mais de 12 mas menos de 20 segundos; (4) – Capaz de elevar o membro inferior sem ajuda, e de manter a posição durante 20 segundos.

4. Permanecer de olhos fechados e a pés juntos numa superfície de espuma

(0) – Incapaz de subir para a superfície de espuma ou de manter a posição, sem ajuda, e de manter os olhos abertos; (1) – Capaz de subir para a superfície de espuma ou de manter a posição, sem ajuda, mas incapaz ou pouco disposto a fechar os olhos; (2) – Capaz de subir para a superfície de espuma ou de manter a posição, sem ajuda, com os olhos fechados durante 10 segundos ou menos; (3) – Capaz de subir para a superfície de espuma ou de manter a posição, sem ajuda, com os olhos fechados mais de 10 segundos e menos de 20 segundos; (4) – Capaz de subir para a superfície de espuma ou de manter a posição, sem ajuda, com os olhos fechados durante 20 segundos.

Senior Fitness Test (Rikli & Jones, 2001)

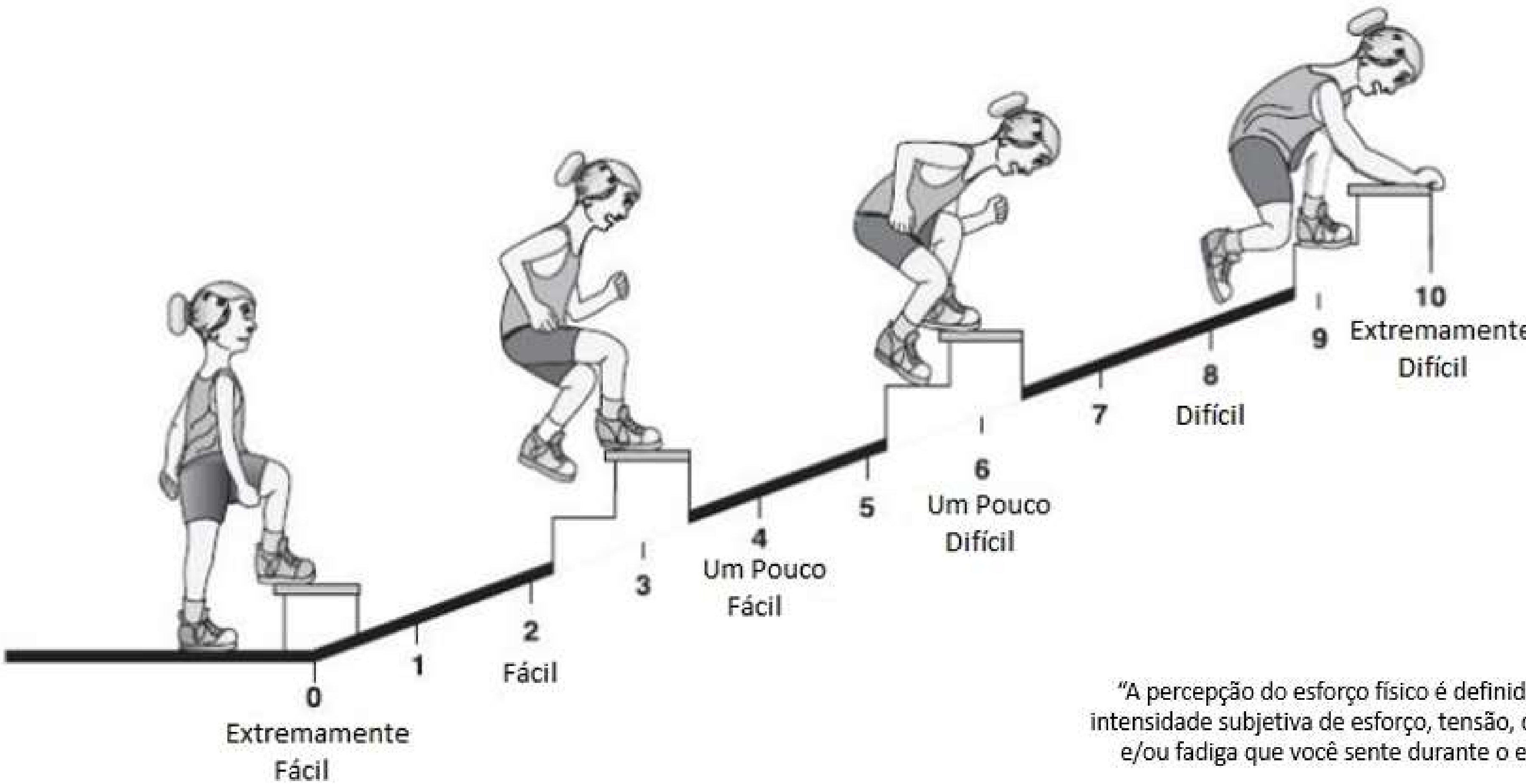
Levantar e sentar na cadeira	CST	[ ][ ]		n
Flexão do braço	ACT	[ ][ ]		n
Sentar e alcançar o pé	CSAR	[ ][ ][ ].[ ]	[ ][ ][ ].[ ]	cm
Alcançar atrás das costas	BST	[ ][ ][ ].[ ]	[ ][ ][ ].[ ]	cm
Levantar e Caminhar (8-foot)	FUG	[ ][ ].[ ][ ]	[ ][ ].[ ][ ]	seg
Andar 6 minutos	6 MWT	[ ][ ][ ][ ]		m
Dinamometria Manual	HANDG	[ ][ ] kg	[ ][ ]	kg

Antropometria e composição corporal

Massa Corporal (kg)	WT	[ ][ ][ ].[ ]			
Altura (cm)	HT	[ ][ ][ ].[ ]	[ ][ ][ ].[ ]	[ ][ ][ ].[ ]	5 mm
P. Cintura	WACI	[ ][ ].[ ]	[ ][ ].[ ]	[ ][ ].[ ]	5 mm

Gord. [ ][ ].[ ] Gord. Visceral [ ][ ].[ ] M. Muscular [ ][ ].[ ] Taxa Metab. Rep. [ ][ ].[ ]

Como foi o exercício?



"A percepção do esforço físico é definida como a intensidade subjetiva de esforço, tensão, desconforto e/ou fadiga que você sente durante o exercício"

Appendix B
Cognitive Assessment Tools

- Mini-Mental State Examination (MMSE)
- Addenbroke's Cognitive Examination (ACE)
- Digit Symbol Coding Subtest (Wechsler Adult Intelligence Scale – WAIS III)
- Letter Number Sequencing (Wechsler Adult Intelligence Scale – WAIS III)

MINI EXAME DO ESTADO MENTAL

Orientação Temporal Espacial – questão 2.a até 2.j pontuando 1 para cada resposta correta, máximo de 10 pontos.
Registros – questão 3.1 até 3.d pontuação máxima de 3 pontos.
Atenção e cálculo – questão 4.1 até 4.f pontuação máxima 5 pontos.
Lembrança ou memória de evocação – 5.a até 5.d pontuação máxima 3 pontos.
Linguagem – questão 5 até questão 10, pontuação máxima 9 pontos.

Identificação do cliente
Nome:____
Data de nascimento/idade: ______ Sexo:______________
Escolaridade: Analfabeto ( ) 0 à 3 anos ( ) 4 à 8 anos ( ) mais de 8 anos ( )
Avaliação em: ____/____/____ Avaliador: ____________________.

Pontuações máximas

Orientação Temporal Espacial
1. Qual é o (a) Dia da semana?__ 1
Dia do mês?______ 1
Mês?_______ 1
Ano?______ 1
Hora aproximada?___ 1
2. Onde estamos?
Local?______ 1
Instituição (casa, rua)?___ 1
Bairro?______ 1
Cidade?_______ 1
Estado?______ 1

Registros
1. Mencione 3 palavras levando 1 segundo para cada uma. Peça ao paciente para repetir as 3 palavras que você menciou. Estabeleça um ponto para cada resposta correta.

-Vaso, carro, tijolo
________ 3

3. Atenção e cálculo
Sete seriado (100-7=93-7=86-7=79-7=72-7=65). Estabeleça um ponto para cada resposta correta. Interrompa a cada cinco respostas. Ou soletrar apalavra MUNDO de trás para frente.
________ 5

4. Lembranças (memória de evocação)
Pergunte o nome das 3 palavras aprendidos na questão 2. Estabeleça um ponto para cada resposta correta.
________ 3

Pontuações máximas

Linguagem
5. Aponte para um lápis e um relógio. Faça o paciente dizer o nome desses objetos conforme você os aponta
_______ 2

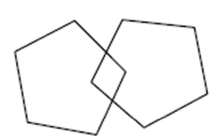
6. Faça o paciente. Repetir "nem aqui, nem ali, nem lá".
______ 1

7. Faça o paciente seguir o comando de 3 estágios. "Pegue o papel com a mão direita. Dobre o papel ao meio. Coloque o papel na mesa".
_____ 3

8. Faça o paciente ler e obedecer ao seguinte:
FECHE OS OLHOS.
_____ 1

09. Faça o paciente escrever uma frase de sua própria autoria. (A frase deve conter um sujeito e um objeto e fazer sentido).
(Ignore erros de ortografia ao marcar o ponto)
_____ 1

10. Copie o desenho abaixo.
Estabeleça um ponto se todos os lados e ângulos forem preservados e se os lados da interseção formarem um quadrilátero.
________ 1



AVALIAÇÃO do escore obtido	TOTAL DE PONTOS OBTIDOS ______
Pontos de corte – MEEM Brucki et al. (2003) 20 pontos para analfabetos 25 pontos para idosos com um a quatro anos de estudo 26,5 pontos para idosos com cinco a oito anos de estudo 28 pontos para aqueles com 9 a 11 anos de estudo 29 pontos para aqueles com mais de 11 anos de estudo.	

Referências

Folstein MF, Folstein SE, McHugh PR. Mini-Mental State: a practical method for grading the cognitive state of patients for clinician. J Psychiatr Res 1975;12:189-198.

Bertolucci PHF et al. O Mini-Exame do Estado Mental em uma população geral: impacto da escolaridade. Arquivos de Neuro-Psiquiatria, 1994, 52(1):1-7.

Brucki SMD et al. Sugestões para o uso do Mini-Exame do Estado Mental no Brasil. Arquivos de Neuro-Psiquiatria, 2003, 61(3):777-781 B.

Tabela para apresentação dos resultados do MINIMENTAL

MINI EXAME DO ESTADO MENTAL									
Teste	**Idade no teste**	**Orien. Tem./Espac.**	**Registros**	**Atenção e cálculo**	**Lembrança**	**Linguagem**	**Total**	**Classificação**	**Data**

cegoc

Código – Tarefa de Codificação

1	2	3	4	5	6	7	8	9
—	⊥	┘	└	∪	○	Λ	×	=

Exemplo

2	1	3	7	2	4	8	2	1	3	2	1	4	2	3	5	2	3	1	4

5	6	3	1	4	1	5	4	2	7	6	3	5	7	2	8	5	4	6	3

7	2	8	1	9	5	8	4	7	3	6	2	5	1	9	2	8	3	7	4

6	5	9	4	8	3	7	2	6	1	5	4	6	3	7	9	2	8	1	7

9	4	6	8	5	9	7	1	8	5	2	9	4	8	6	3	7	9	8	6

2	7	3	6	5	1	9	8	4	5	7	3	1	4	8	7	9	1	4	5

7	1	8	2	9	3	6	7	2	8	5	2	3	1	4	8	4	2	7	6

efa de Aprendizagem Incidental

E.

5	1	8	2	9	4	6	3	7

8	5	6	3	1	9	4	7	2

M. L.

13. SUBTESTE SEQUÊNCIAS DE LETRAS E NÚMEROS

CRITÉRIO DE INTERRUPÇÃO	COTAÇÃO
Após insucesso nos **três ensaios** de um mesmo Item.	**Por ensaio**: 0 ou 1 ponto; **Por Item**: Ensaio 1 + Ensaio 2 + Ensaio 3.

		SEQUÊNCIA	RESPOSTA	Cotação por Ensaio		Cotação por Item (0, 1, 2 ou 3)
Item 1	Ensaio 1	**L – 2**	2 – L	0	1	
	Ensaio 2	**6 – P**	6 – P	0	1	
	Ensaio 3	**B – 5**	5 – B	0	1	
Item 2	Ensaio 1	**F – 7 – L**	7 – F – L	0	1	
	Ensaio 2	**R – 4 – D**	4 – D – R	0	1	
	Ensaio 3	**H – 1 – 8**	1 – 8 – H	0	1	
Item 3	Ensaio 1	**T – 9 – A – 3**	3 – 9 – A – T	0	1	
	Ensaio 2	**V – 1 – J – 5**	1 – 5 – J – V	0	1	
	Ensaio 3	**7 – N – 4 – L**	4 – 7 – L – N	0	1	
Item 4	Ensaio 1	**8 – D – 6 – G – 1**	1 – 6 – 8 – D – G	0	1	
	Ensaio 2	**L – 2 – C – 7 – S**	2 – 7 – C – L – S	0	1	
	Ensaio 3	**5 – P – 3 – Z – 9**	3 – 5 – 9 – P – Z	0	1	
Item 5	Ensaio 1	**M – 4 – E – 7 – Q – 2**	2 – 4 – 7 – E – M – Q	0	1	
	Ensaio 2	**X – 8 – H – 5 – F – 3**	3 – 5 – 8 – F – H – X	0	1	
	Ensaio 3	**6 – G – 9 – A – 2 – S**	2 – 6 – 9 – A – G – S	0	1	
Item 6	Ensaio 1	**R – 3 – B – 4 – Z – 1 – C**	1 – 3 – 4 – B – C – R – Z	0	1	
	Ensaio 2	**5 – T – 9 – J – 2 – X – 7**	2 – 5 – 7 – 9 – J – T – X	0	1	
	Ensaio 3	**E – 1 – H – 8 – R – 4 – D**	1 – 4 – 8 – D – E – H – R	0	1	
Item 7	Ensaio 1	**5 – H – 9 – S – 2 – N – 6 – A**	2 – 5 – 6 – 9 – A – H – N – S	0	1	
	Ensaio 2	**D – 1 – R – 9 – B – 4 – L – 3**	1 – 3 – 4 – 9 – B – D – L – R	0	1	
	Ensaio 3	**7 – M – 2 – T – 6 – F – 1 – Z**	1-2-6-7 – F – M – T – Z	0	1	

PONTUAÇÃO TOTAL OBTIDA (MÁXIMO = 21)	

Wechsler Memory Scale (WMS–III; Wechsler, 1997)*

Subteste: Sequência Letras-Números
(traduzido para português e adaptado para investigação por Susana Fernandes, 2007, revisão de Salomé Pinho, 2007)

Instruções

Dizer "vou dizer um grupo de números e de letras. Depois disso, gostaria que me dissesse primeiro os números, por ordem, a começar no número mais pequeno. Depois diga as letras pela ordem alfabética. Por exemplo, se eu disser B-7, a sua resposta deverá ser 7-B. Primeiro vem o número e depois a letra. Se eu disser 9-C-3, deverá responder a seguir 3-9-C, os números por ordem primeiro e depois as letras pela ordem alfabética. Vamos fazer uns ensaios de treino."

Aplicar todos os ensaios de treino. Dizer cada combinação a um ritmo de um número ou uma letra por segundo. Permita ao examinando mais tempo para responder (as respostas correctas estão entre parênteses).

6-F	(6-F)
G-4	(G-4)
3-V-5	(3-5-V)
T-7-L	(7-L-T)
1-J-A	(1-A-J)

Se o examinando comete um erro num dos ensaios de treino, corrija-o e repita as instruções, se for necessário. Mesmo que o examinando falhe todos os ensaios de treino, continue com o subteste.

Prossiga para o item 1. Aplique os itens que estão na folha de registo. Registe as respostas do examinando.

*Ref. Bibliográfica:
Wechsler, D. (1997). Wechsler Memory Scale – Third Edition (WMS-III) stimulus booklet. San Antonio, TX: The Psychological Corporation.

Appendix C
Game User Research Tools

- Game experience survey and Exergames Post Experience
- Subjective Units of Distress Scale (SUDS)
- System Usability Scale

GAME EXPERIENCE SURVEY

Name_____________________________________ Gender_______
Age_______

Time in the Gym __________ Weekly hours of PA __________

Schooling___________ Occupation _______________

1. Have you ever played any game? Yes No
   If yes: Can you mention some of these games?
   ____
   ____
   ____
   ____
2. What attracts you to play these games?
   ____
   ____
   ____
   ____
3. Do you have any idea about what a videogame is?
   No ____ Yes_____
   What____
   ____
   ____
4. Have you ever played any videogame? Yes No
   If No: Why do not you play videogames?
   a. Cost b. Not Interested c. Not enough time d. Opportunity
   e. Lack of skill f. Not allowed

   Others____
   _____

   If No, skip to question # 12

5. How do you play videogames?
   a) Console b) PC- Laptop c) Smartphone or Tablet d) Handheld e) Other
6. How long have you been playing videogames?
   a) 0-6 Months b) 6-12 Months c) More than 1 Year d) More than 5 years

7. How did you get started playing videogames, who or what motivated you to play?
   WHO a) Self-interest b. Family (Who) c. Friends (M, F) d) Partner
   WHAT e) Advertisement f. Internet g) Social Activity (Which) f. Other

8. How often (approximately) do you currently play videogames?
   a) Daily b) Weekly c) Once a month d) Once in 6 months
   e) Once a year f) less than once a year or never

9. How good are you at playing videogames?
   a) very good b) moderately good c) not very skilled d) no skill

10. What are your Top 3 genres, or videogame categories that you enjoy to play?
    #1________________ #2_______________ #3________________

11. What are your top 3 videogames ever?
    #1_________________ #2_______________ #3_______________

12. Based on your top 3, what attracts you to play these games?
____
____
____
____

13. Would you be interest in playing videogames in the future? Yes No
Why____
____
____
____
____

14. What would you like to see in a videogame made just for YOU?
____
____
____
____

____
____

AHA Exergames Post Experience

1. If you had the opportunity to travel (first time or again) in Portugal… Where will you go and why?
   Where____
   Why____

2. What activities do you normally enjoy doing in your "free-time"?

3. "Carrinho de Cestos" Experience. Feedback

   a) Please mention 3 things you like

   b) Please mention 3 things you dislike

   c) Please mention 3 things you would like to add/remove for the game

4. "Grape Stomping" Experience. Feedback

   d) Please mention 3 things you like

   e) Please mention 3 things you dislike

   f) Please mention 3 things you would like to add/remove for the game

5. "Rabelos VR" Experience. Feedback

   g) Please mention 3 things you like

h) Please mention 3 things you dislike

____________________ _______________________ _____________________

i) Please mention 3 things you would like to add/remove for the game

____________________ _______________________ _____________________

6. "Exerfado" Experience. Feedback

j) Please mention 3 things you like

____________________ ______________________ _____________________

k) Please mention 3 things you dislike

____________________ _______________________ _____________________

l) Please mention 3 things you would like to add/remove for the game

____________________ _______________________ _____________________

7. In which aspect do you think these Exergames can be useful for you:
a) Physical Health b) Mental Health c) Social Interaction d) Pure Enjoyment

d) Escape for daily Routine

8. Would you like to see this technology integrated in the gym? Yes No
Why?

____
____
____

How?

____
____
____

The distress thermometer –
Subjective Units of Distress Scale (SUDS)

Try to get used to rating your distress, fear, anxiety or discomfort on a scale of 0-100. Imagine you have a 'distress thermometer' to measure your feelings according to the following scale. Notice how your level of distress and fear changes over time and in different situations.

100	Highest distress/fear/anxiety/discomfort that you have ever felt
90	Extremely anxious/distressed
80	Very anxious/distressed, can't concentrate
70	Quite anxious/distressed, interfering with performance
60	
50	Moderate anxiety/distress, uncomfortable but can continue to perform
40	
30	Mild anxiety/distress, no interference with performance
20	Minimal anxiety/distress
10	Alert and awake, concentrating well
0	Totally relaxed

Participant ID: _____ Site: ______________________ Date: ___/___/___

System Usability Scale

Instructions: For each of the following statements, mark <u>one</u> box that best describes your reactions to the website *today*.

		Strongly Disagree				Strongly Agree
1.	I think that I would like to use this website frequently.	☐	☐	☐	☐	☐
2.	I found this website unnecessarily complex.	☐	☐	☐	☐	☐
3.	I thought this website was easy to use.	☐	☐	☐	☐	☐
4.	I think that I would need assistance to be able to use this website.	☐	☐	☐	☐	☐
5.	I found the various functions in this website were well integrated.	☐	☐	☐	☐	☐
6.	I thought there was too much inconsistency in this website.	☐	☐	☐	☐	☐
7.	I would imagine that most people would learn to use this website very quickly.	☐	☐	☐	☐	☐
8.	I found this website very cumbersome/awkward to use.	☐	☐	☐	☐	☐
9.	I felt very confident using this website.	☐	☐	☐	☐	☐
10.	I needed to learn a lot of things before I could get going with this website.	☐	☐	☐	☐	☐

Positive and Negative Affect Schedule

Encontra a seguir uma lista de palavras, que representam diferentes sentimentos e emoções. Indique o quanto experienciou esses sentimentos e emoções, na semana passada. Por favor, marque uma cruz (X) no quadrado que melhor indica a sua resposta.

	1 Muito Pouco ou nada	2 Um Pouco	3 Assim, assim	4 Muito	5 Muitíssimo
1. Interessado (a)					
2. Aflito (a)					
3. Estimulado (animado)					
4. Aborrecido (a)					
5. Forte					
6. Culpado (a)					
7. Assustado (a)					
8. Hostil (inimigo)					
9. Entusiasmado (arrebatado)					
10. Orgulhoso (a)					
11. Irritável					
12. Atento (a)					
13. Envergonhado (a)					
14. Inspirado (a)					
15. Nervoso (a)					
16. Decidido (a)					
17. Atencioso (a)					
18. Agitado (inquieto)					
19. Activo (mexido)					
20. Medroso (a)					
21. Emocionado (a)					
22. Magoado (a)					

Appendix D
Consent Forms

- Inform Consent (study reported section 6.1)
- Inform Consent (study reported section 6.2)
- Inform Consent (study reported section 6.3)

Consentimento informado para participação em pesquisa

Título do estudo: Videojogos de exercício e respostas corporais
Principal Investigator: John Muñoz. Estudante de Doutoramento
Supervisores: Professores Sergi Bermudez, Élvio Gouveia e Mónica Cameirão
Colaboradores: Teresa Paulino
Universidade da Madeira. Instituto de Tecnologias Interativas da Madeira

Objetivo deste estudo

O objetivo deste estudo é avaliar as respostas do corpo durante uma curta interação com um Videojogo de Exercício.

Procedimentos

Foi convidado(a) para participar numa experiência científica do grupo de investigação Neurorehab Lab do Instituto de Tecnologias Interativas da Madeira. A sessão terá lugar no Ginásio do Centro Cívico de Santo António. Para a experiência são necessárias duas sessões de aproximadamente 30 minutos (incluindo ligações e instruções) realizadas no mesmo dia. Para o procedimento, em primeiro lugar, vamos conectar-lhe um dispositivo que mede a atividade elétrica do seu corpo, especificamente do seu coração e da sua pele. Depois de verificar as conexões, para ter certeza de que a posição dos elétrodos do sistema estão na posição correta, se-lhe-á dado um conjunto de instruções para jogar um videojogo projetado no chão. Durante as tarefas registaremos um eletrocardiograma (ECG) e sinais de atividade electrodermal (EDA). Tente executar as tarefas o melhor que conseguir no tempo que lhe for indicado. Nesta experiência terá de usar um joystick (comando para videojogos de fácil utilização) bem como alguns movimentos para interagir com o videojogo. Iremos pedir-lhe que preencha dois questionários no fim de cada sessão. Eventualmente a sua interação com o videojogo poderá ser gravada. Todos os dados recolhidos serão processados de tal forma que o seu anonimato será sempre preservado.

Requerimentos para participação

É considerado elegível para participar se: 1) não teve nenhuma lesão recente nos seus membros inferiores ou superiores, 2) ser capaz de se manter de pé sem ajuda, 3) não tem nenhum distúrbio neurológico.

Riscos

O risco associado com a participação neste estudo é idêntico ao encontrado na vida diária ou durante a realização de uma atividade normal de exercício físico (por exemplo, simples alongamentos musculares). Os elétrodos ECG e EDA são superficiais e não representam qualquer risco para a sua saúde. A interação com o videojogo requer a execução de repetições (físicas e mentais) com um pequeno dispositivo no seu corpo. Poderá sentir um ligeiro cansaço ou dor de cabeça nalguma sessão.

Benefícios
O estudo contribuirá para o desenvolvimento de novas ferramentas para exercício físico e reabilitação que no futuro ajudarão a população idosa e doentes com diferentes deficiências cognitivas e/ou motoras.

Confidencialidade
Ao participar neste estudo, compreende e concorda que o NeuroRehab Lab pode ser obrigado a divulgar o seu formulário de consentimento, dados e outras informações pessoalmente identificáveis como exigido por lei, regulação, intimação ou ordem judicial. Caso contrário, o seu sigilo será mantido da seguinte maneira: dados e outras informações recolhidas durante este estudo poderão ser utilizadas pelo Neurorehab Lab e publicadas e/ou divulgadas a outros do Neurorehab Lab para fins de investigação. No entanto, as suas informações pessoais nunca serão reveladas em qualquer publicação ou divulgação dos dados de pesquisa e/ou resultados pelo Neurorehab Lab.

Consentimento informado para participação em pesquisa

Eu compreendo que todas as informações obtidas no estudo **“Videojogos de exercício e respostas corporais**” pertence à equipa de investigação responsável. Dou o meu consentimento para recolha anónima dos meus dados (resultados, fotografias e videos), que serão armazenados e processados para avaliação cientìfica. Compreendo a importância desta informação, e todas as questões que apresentei foram respondidas satisfatoriamente. Ttive o tempo necessário para decidir sobre a minha participação neste estudo e sendo assim consinto com a minha participação e recolha de informação.

______________________________________ ____________

Assinatura do participante Data

______________________________________ ____________

Assinatura do Investigador Data

Consentimento informado para participação em pesquisa

Título do estudo: Videojogos de exercício e respostas corporais

Principal Investigator: John Muñoz. Estudante de Doutoramento

Supervisores: Professores Sergi Bermudez, Élvio Gouveia e Mónica Cameirão

Colaboradores: Honorato Sousa, Lucy Conceição, Teresa Paulino

Universidade da Madeira. Instituto de Tecnologias Interativas da Madeira

Objetivo deste estudo

O objetivo deste estudo é avaliar as respostas do corpo durante uma interação com um Videojogo de Exercício durante 6 semanas.

Procedimentos

Foi convidado(a) para participar numa experiência científica do grupo de investigação Neurorehab Lab do Instituto de Tecnologias Interativas da Madeira. A sessão terá lugar no Ginásio de São Martinho. Para a experiência são necessárias tres sessões de aproximadamente 60 minutos (incluindo ligações e instruções) realizadas em dias diferentes cada semana (6 semanas no total). Para o procedimento, em primeiro lugar, vamos conectar-lhe um dispositivo que mede a atividade elétrica do seu corpo, especificamente do seu coração. Depois de verificar as conexões, para ter certeza de que a posição dos elétrodos do sistema estão na posição correta, se-lhe-á dado um conjunto de instruções para jogar um videojogo projetado no chão. Durante as tarefas registaremos um eletrocardiograma (ECG). Tente executar as tarefas o melhor que conseguir no tempo que lhe for indicado. Nesta experiência terá de usar alguns movimentos para interagir com o videojogo. Iremos pedir-lhe a sua opinião sobre o nível de fadiga físicano ao fim de cada sessão. Eventualmente a sua interação com o videojogo poderá ser gravada. Todos os dados recolhidos serão processados de tal forma que o seu anonimato será sempre preservado.

Requerimentos para participação

É considerado elegível para participar se: 1) não teve nenhuma lesão recente nos seus membros inferiores ou superiores, 2) ser capaz de se manter de pé sem ajuda, 3) não tem nenhum distúrbio neurológico o cardíaco.

Riscos

O risco associado com a participação neste estudo é idêntico ao encontrado na vida diária ou durante a realização de uma atividade normal de exercício físico (por exemplo, simples alongamentos musculares). Os elétrodos ECG são superficiais e não representam qualquer risco para a sua saúde. A interação com o videojogo requer a execução de repetições (físicas e mentais) com um pequeno dispositivo no seu corpo. Poderá sentir um ligeiro cansaço ou dor de cabeça nalguma sessão.

Benefícios

O estudo contribuirá para o desenvolvimento de novas ferramentas para exercício físico e reabilitação que no futuro ajudarão a população idosa e doentes com diferentes deficiências cognitivas e/ou motoras.

Confidencialidade

Ao participar neste estudo, compreende e concorda que o NeuroRehab Lab pode ser obrigado a divulgar o seu formulário de consentimento, dados e outras informações pessoalmente identificáveis como exigido por lei, regulação, intimação ou ordem judicial. Caso contrário, o seu sigilo será mantido da seguinte maneira: dados e outras informações recolhidas durante este estudo poderão ser utilizadas pelo Neurorehab Lab e publicadas e/ou divulgadas a outros do Neurorehab Lab para fins de investigação. No entanto, as suas informações pessoais nunca serão reveladas em qualquer publicação ou divulgação dos dados de pesquisa e/ou resultados pelo Neurorehab Lab. Finalmente, os dados fisiológicos relacionados aos registros de ECG serão publicados anonimamente em uma base de dados que estará disponível na plataforma ResearchGate.

Consentimento informado para participação em pesquisa

Eu compreendo que todas as informações obtidas no estudo **“Videojogos de exercício e respostas corporais**” pertence à equipa de investigação responsável. Dou o meu consentimento para recolha anónima dos meus dados (resultados, fotografias e videos), que serão armazenados e processados para avaliação cientìfica. Compreendo a importância desta informação, e todas as questões que apresentei foram respondidas satisfatoriamente. Ttive o tempo necessário para decidir sobre a minha participação neste estudo e sendo assim consinto com a minha participação e recolha de informação.

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Assinatura do participante Data

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Assinatura do Investigador Data

Consentimento informado para participação em pesquisa

Título do estudo: Videojogos de exercício e respostas corporais
Principal Investigator: John Muñoz. Estudante de Doutoramento
Supervisores: Professores Sergi Bermudez, Élvio Gouveia e Mónica Cameirão
Colaboradores: Fabio Pereira
Universidade da Madeira. Instituto de Tecnologias Interativas da Madeira

Objetivo deste estudo

O objetivo deste estudo é avaliar as respostas do corpo durante uma curta interação com um Videojogo de Exercício.

Procedimentos

Foi convidado(a) para participar numa experiência científica do grupo de investigação Neurorehab Lab do Instituto de Tecnologias Interativas da Madeira. A sessão terá lugar no Ginásio do Centro Cívico de Santo António. Para a experiência são necessárias tres sessões de aproximadamente 40 minutos (incluindo ligações e instruções) realizadas em dias diferentes. Para o procedimento, em primeiro lugar, vamos conectar-lhe um dispositivo que mede a atividade elétrica do seu corpo, especificamente do seu coração e da sua pele. Depois de verificar as conexões, para ter certeza de que a posição dos elétrodos do sistema estão na posição correta, se-lhe-á dado um conjunto de instruções para jogar um videojogo projetado no chão. Durante as tarefas registaremos um eletrocardiograma (ECG). Tente executar as tarefas o melhor que conseguir no tempo que lhe for indicado. Nesta experiência terá de usar alguns movimentos para interagir com o videojogo. Iremos pedir-lhe que preencha dois questionários no fim de cada sessão. Eventualmente a sua interação com o videojogo poderá ser gravada. Todos os dados recolhidos serão processados de tal forma que o seu anonimato será sempre preservado.

Requerimentos para participação

É considerado elegível para participar se: 1) não teve nenhuma lesão recente nos seus membros inferiores ou superiores, 2) ser capaz de se manter de pé sem ajuda, 3) não tem nenhum distúrbio neurológico.

Riscos

O risco associado com a participação neste estudo é idêntico ao encontrado na vida diária ou durante a realização de uma atividade normal de exercício físico (por exemplo, simples alongamentos musculares). Os elétrodos ECG são superficiais e não representam qualquer risco para a sua saúde. A interação com o videojogo requer a execução de repetições (físicas e mentais) com um pequeno dispositivo no seu corpo. Poderá sentir um ligeiro cansaço ou dor de cabeça nalguma sessão.

Benefícios

O estudo contribuirá para o desenvolvimento de novas ferramentas para exercício físico e reabilitação que no futuro ajudarão a população idosa e doentes com diferentes deficiências cognitivas e/ou motoras.

Confidencialidade

Ao participar neste estudo, compreende e concorda que o NeuroRehab Lab pode ser obrigado a divulgar o seu formulário de consentimento, dados e outras informações pessoalmente identificáveis como exigido por lei, regulação, intimação ou ordem judicial. Caso contrário, o seu sigilo será mantido da seguinte maneira: dados e outras informações recolhidas durante este estudo poderão ser utilizadas pelo Neurorehab Lab e publicadas e/ou divulgadas a outros do Neurorehab Lab para fins de investigação. No entanto, as suas informações pessoais nunca serão reveladas em qualquer publicação ou divulgação dos dados de pesquisa e/ou resultados pelo Neurorehab Lab.

Consentimento informado para participação em pesquisa

Eu compreendo que todas as informações obtidas no estudo **“Videojogos de exercício e respostas corporais**” pertence à equipa de investigação responsável. Dou o meu consentimento para recolha anónima dos meus dados (resultados, fotografias e videos), que serão armazenados e processados para avaliação cientìfica. Compreendo a importância desta informação, e todas as questões que apresentei foram respondidas satisfatoriamente. Ttive o tempo necessário para decidir sobre a minha participação neste estudo e sendo assim consinto com a minha participação e recolha de informação.

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Assinatura do participante Data

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Assinatura do Investigador Data

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