Universidade do Minho
Escola de Medicina

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Characterization of a wearable monitoring system of physical activity as a surrogate of brain structure and function in older populations

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Tese de Doutoramento
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Trabalho efetuado sob a orientação da
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Professor Doutor José Miguel Gomes Moreira Pêgo

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STATEMENT OF INTEGRITY

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

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

Assinado por : **CÉLIA MARGARIDA VIEGAS DOMINGOS**
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CARTÃO DE CIDADÃO

CARACTERIZAÇÃO DE UM SISTEMA DE MONITORIZAÇÃO DE ATIVIDADE FÍSICA COMO SUBSTITUTO DA ESTRUTURA E FUNÇÃO DO CÉREBRO EM IDOSOS

RESUMO

O envelhecimento cerebral saudável é um fator determinante do estado de saúde e da qualidade de vida da população idosa. Estudos tem demonstrado que a atividade física (AF) pode melhorar a saúde cerebral. Contudo, o uso de medidas subjetivas de AF e a ausência de abordagens multimodais de neuroimagem têm limitado a compreensão dos mecanismos associados.

Nesta tese, pretendemos realizar um estudo observacional transversal em idosos para (i) comparar estimativas objetivas de AF com dados obtidos a partir de questionários em idosos residentes na comunidade; (ii) avaliar o perfil de AF e suas associações com variáveis relativas a indicadores de saúde; (iii) testar a aceitação, usabilidade e satisfação de um sistema de monitorização de AF (Xiaomi Mi Band 2®); e (iv) explorar associações entre AF e a estrutura e função do cérebro através da avaliação objetiva da AF e aquisições de neuroimagem. Esta abordagem foi complementada por uma análise sistemática de estudos de neuroimagem observacionais que avaliaram a relação entre PA e a estrutura e função do cérebro em idosos sem doença cognitiva ou neuropatológica.

Os resultados evidenciaram uma grande variação do tempo sedentário e AF entre as medidas subjetivas (auto-relato) e as correspondentes medidas objetivas (Xiaomi Mi Band 2®), verificando-se a maior diferença para a estimativa do tempo sedentário. Adicionalmente, verificámos que a AF auto-relatada e medida objetivamente associam-se de forma diferente com as variáveis relativas a indicadores de saúde. Neste estudo verificou-se também que o Xiaomi Mi Band® apresenta um excelente nível de aceitação, usabilidade e satisfação entre os idosos, sugerindo que este dispositivo é adequado para esta população. Além disso, verificámos que a usabilidade é um fator importante na determinação da satisfação do utilizador. Por fim, observou-se uma correlação positiva significativa entre a AF vigorosa e o volume do giro parahipocampal esquerdo e do hipocampo direito. Além disso, foi observada uma maior conectividade funcional (CF) entre o giro frontal, o giro cingulado, o lobo inferior occipital e a AF de intensidade leve, moderada e total e menor CF associada ao tempo sedentário para as mesmas redes. Concluindo, os resultados sugerem que dispositivos com características semelhantes ao Xiaomi Mi Band® podem ser sistemas de monitorização de AF viáveis, podendo ser implementados com sucesso em estratégias de promoção de AF para a adoção de um estilo de vida fisicamente ativo. Além disso, os benefícios de um estilo de vida fisicamente ativo podem resultar numa melhor saúde cerebral.

Palavras-chave: Atividade física; dispositivos móveis; envelhecimento; experiência do utilizador; saúde cerebral.

CHARACTERIZATION OF A WEARABLE MONITORING SYSTEM OF PHYSICAL ACTIVITY AS A SURROGATE OF BRAIN STRUCTURE AND FUNCTION IN OLDER POPULATIONS

ABSTRACT

Healthy brain aging is one of the most important determinants of health status and quality of life in the older population. There is increasing evidence that physical activity (PA) contributes to brain health. However, the lack of use of integrative approaches including PA objective measures and multimodal neuroimaging has limited the knowledge of the mechanisms underlying the association.

In this thesis, we aimed to conduct an observational cross-sectional study with community-dwelling older adults to (i) compare PA objective estimates with data obtained from self-report questionnaires; (ii) assess PA profiles and their associations with health outcomes; (iii) test acceptability, usability, and user satisfaction of a commercially available wearable PA monitoring system (Xiaomi Mi Band 2®); and (iv) explore the associations between objectively measured PA and brain structure and function. This approach was complemented by a systematic review of observational neuroimaging studies that have examined the relationship between PA and brain structure and function in older adults without cognitive disease or neuropathology.

Altogether, the findings highlighted the large variation between subjective (self-reported) and objectively measured PA (Xiaomi Mi Band 2®) and sedentary time parameters, with the highest difference found for the latter. Additionally, self-reported and objectively measured PA were differently associated with health outcomes (cognitive and mood profiles, anthropometric, body composition, and physical performance measures). Findings also demonstrated that the Xiaomi Mi Band® has an excellent level of acceptability, usability, and satisfaction among older adults, suggesting that this device is suitable for this population. Moreover, usability was noted to be an important factor influencing user satisfaction. Finally, a significant positive correlation was found between the time spent in vigorous PA and the left parahippocampal gyrus and right hippocampus volumes. Findings also revealed higher functional connectivity (FC) between the frontal gyrus, cingulate gyrus, and occipital inferior lobe for light, moderate, and total PA time, and sedentary time associated with lower FC in the same networks.

In conclusion, these results suggest that wearables with characteristics similar to the Xiaomi Mi Band® may be a feasible monitoring system of PA. Thus, these types of devices may be used to create PA promotion strategies for the adoption of a physically active lifestyle in older populations. Moreover, the benefits of having a physically active lifestyle may translate into better brain health.

Keywords: Aging; brain health; physical activity; user experience; wearable device.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

A

ACSM: The American College of Sports Medicine

AD: Alzheimer's disease

AD: Axial Diffusivity

ADL: Activities of Daily Living

APOE-ε4: apolipoproteinE-ε4

AVLT: Rey Auditory Verbal Learning Test

B

BCM: Body Cell Mass

BDNF: Brain-derived neurotrophic factor

BI: Behavioral intention

BMI: Body mass index

BNT: 30-item Boston Naming Test

BOLD: Blood oxygen level-dependent

BP: Blood pressure

BP: Bodily pain

BPHQ: Brief patient health questionnaire

BVMT-R/PAL: Brief Visuospatial Memory Test-Revised and the Paired Associates Learning

BVRT: Benton Visual Retention Test

C

C.R.: Critical ratio

C: Color

CANTAB: Cambridge Neuropsychological Test Automated Battery

CANX: Computer anxiety

CDR: Clinical Dementia Rating

CERAD: The consortium to establish a registry for Alzheimer's disease

CES-D: Center for Epidemiologic Studies Depression Scale

CFA: Confirmatory factor analysis

CFI: Comparative Fit Index

CHAMPS: Community Healthy Activities Model Program for Seniors

CLTR: Consistent long-term retrieval

COWAT: Controlled Oral Word Association Test

CSF: Cerebrospinal fluid

CVLT: California Verbal Learning Test

D

D-KEFS: Delis-Kaplan Executive Function System

DMN: Default mode network

DQ: Dementia Questionnaire

DR: Delayed recall

DRS-2: Mattis Dementia Rating Scale 2

DS: Digits Span Test

DSB: Digit Span Backwards

DSST: Digit Symbol Substitution Test

DTI: Diffusion-tensor imaging

DVARS: Derivative of root mean square variance over voxels

DWM: Deep white matter

E

EE: Energy expenditure

EEG: Electroencephalography

EFA: Exploratory factor analysis

F

FA: Fractional anisotropy

FAT: Body fat

FC: Functional connectivity

FD: Framewise displacement

FFM: Free fat mass

fMRI: Functional magnetic resonance imaging

fNIRS: Functional near-infrared spectroscopy

FWE-R: Family-wise error rate

G

GDS Geriatric Depression Scale

GFI: Goodness of Fit Index

GH: General health

GM: Grey matter

GMd: GM density

H

$h.d^{-1}$: Hours per day

HF: Higher fit

HP: Hip circumference

HR: Heart rate

I

IADL: Instrumental Activities of Daily Living

IED: Extra-dimensional Shift

IL-6: Interleukin 6

INU: Intensity non-uniformity

IPAQ: International Physical Activity Questionnaire

IPAQ-SF: International Physical Activity Questionnaire-Short Form

IQ-CODE: The Informant Questionnaire on Cognitive Decline in the Elderly

K

kcal: Kilocalorie

$kcal.wk^{-1}$: Kilocalorie per week

Ke: Cluster extent

K-MMSE: Korean version of the Mini Mental Status Examination

KMO: Kaiser-Meyer-Olkin

L

LF: Lower fit

LTEQ: Leisure-Time Exercise Questionnaire

LTPAQ: Lifetime Total Physical Activity Questionnaire

LTS: Long term storage

M

M: mean

MAQ: Modifiable Activity Questionnaire

MCI: Mild Cognitive Impairment

MCS: Mental component summary

MD: Mean Diffusivity

Mdn: Median

METs: Metabolic equivalent of task

$MET.min.d^{-1}$: Metabolic equivalent of task minutes per day.

MH: Mental health

mHealth: Mobile Health

min.d^{-1}: Minutes per day

min.wk^{-1}: Minutes per week

Mineral: Mineral body density

MINI: MINI International Neuropsychiatric Interview

MLTEQ: Leisure-Time Exercise Questionnaire

MLTPAQ: Minnesota Leisure Time Physical Activity Questionnaire

MMSE: Mini Mental State Examination

MNI: Montreal Neurological Institute

MRI: Magnetic Resonance Imaging

MV-PA: Moderate to vigorous activity

N

n: Frequency

NBS: Network Based Statistics

P

PA: Physical activity

PAO: Physically Active Older

PAR: Physical activity recommendations

PASE: Physical Activity Scale for the Elderly

PCA: Principal components analysis

PCS: Physical component summary

PEC: Perceptions of external control

PEOU: Perceived ease of use

PET: Positron-emission tomography

PF: Physical functioning

PRISMA: Systematic reviews and Meta-Analyses

PRMQ: Prospective and Retrospective Memory Questionnaire

PSSUQ: Post-Study System Usability Questionnaire Usefulness

PU: Perceived usefulness

R

RAVLT: Rey Auditory Verbal Learning Test

RBMT: Rivermead Behavioral Memory Test

RCFT: Rey Complex Figure Test

RE: Role emotional

RMSEA: Root Mean Squared Error of Approximation

ROIs: Region of Interests

RP: Role physical

rs-fMRI: Functional magnetic resonance imaging

RVIP: Rapid Visual Information Processing

S

S.E.: Standard error

SBAS: Stanford Brief Activity Survey

SCID: Structured Clinical Interview for DSM-IV Axis I Disorders

SD: Standard deviation

SDMT: Symbol Digit Modalities Test

SEM: Structural equation modeling

SF: Social functioning

SF-36: Short Form Health Survey

SO: Sedentary Older

SRMR: Standardized Root Mean Squared Residual

SRT: Simple Reaction Time

STW: Spot-the-Word task

SUS: System Usability Scale

T

T1w: T1-weighted

TAM: Technology Acceptance Model

TFCE: Threshold-free cluster enhancement

TICS: The Telephone Interview for Cognitive Status

TIL: Tucker–Lewis Index

TMT: Trail Making Test

TRA: Theory of Reasoned Action

U

USE: Satisfaction and Ease of Use questionnaire

USEQ: User Satisfaction Evaluation Questionnaire

V

VBM: Voxel-based morphometry

VLTM: Verbal Long-term memory

VT: Vitality

W

W: Word

WAIS: Wechsler Abbreviated Scale of Intelligence

WAIS-R: Wechsler Adult Intelligence Scale-Revised

WC: Waist circumference

WHO: World Health Organization

WHR: Waist-to-hip ratio

WM: White matter

WMH: White matter hyperintensities

WTAR: Wechsler Test of Adult Reading WAIS – III

Y

YA: Young Adult

YPAS: Yale Physical Activity Survey

LIST OF FIGURES

CHAPTER I

CHAPTER II

CHAPTER III

CHAPTER IV

CHAPTER V

LIST OF TABLES

CHAPTER I

CHAPTER II

À memória do meu avô por tudo o que representou na minha vida.

"A gratidão é a memória do coração."

Jean Baptiste Massieu

INTRODUCTION

1. Aging & healthy aging

The number of individuals aged 60 or older will grow dramatically in the next three decades being estimated that globally it will surpass two billion by 2050. Notably, the decrease in mortality and lengthening of the average human lifespan has rapidly shifted the worldwide demographic structure towards the elderly. Nonetheless, with the increase in longevity there is a parallel increase in age-related conditions. Therefore, the aging population increases the need for improved social and economic measures necessary to deal with the physiological consequences of the aging process (S. M. Gregory, Parker, & Thompson, 2012; Wu, Wang, Burgess, & Wu, 2013).

Age represents the primary risk factor for chronic diseases, including cardiovascular, malignant, and neurodegenerative conditions (Barnes, 2015; Khan, Singer, & Vaughan, 2017). Additionally, normal aging is associated with changes in brain structure and function, such as cognition, including executive functioning (i.e., abstract thinking, planning, coordination, cognitive flexibility, and working memory) (M. A. Gregory, Gill, & Petrella, 2013), attention, memory, and concentration, as well as physical-related functions such as walking and balance (Sofi et al., 2011). These are consequence of cerebral cortical tissue loss in the frontal, parietal, and temporal lobes (M. A. Gregory et al., 2013; S. M. Gregory et al., 2012; Sofi et al., 2011). Moreover, hippocampal volume loss in older adults has been associated with cognitive impairments (M. A. Gregory et al., 2013; S. M. Gregory et al., 2012). Despite this, age-related cognitive decline can occur as a part of the brain aging processes without leading to dementia, but potentially resulting in a poorer quality of life (Sofi et al., 2011). Still, many cognitive changes may become evident and cause mild disability, even without a state of dementia (S. M. Gregory et al., 2012; Sofi et al., 2011). In other dimensions, the incidence of age-related neurological pathologies has been associated with cardiovascular disease risk factors. For example, high blood pressure contributes to progressive vascular stiffening during aging and is recognized as a primary risk factor associated with age-related reductions in cerebral perfusion and the development of white matter lesions in older individuals (M. A. Gregory et al., 2013). Consequently, longevity has challenged researchers, clinicians, and societal players to develop strategies to promote successful aging (M. A. Gregory et al., 2013). Nowadays, it is imperative to identify feasible, effective, and scalable interventions to mitigate the burden of age-related chronic disease risk and cognitive decline (M. A. Gregory et al., 2013).

The World Health Organization (WHO) defines healthy aging as the process of developing and maintaining the functional ability that enables wellbeing in older age (Beard et al., 2016). Functional ability is described as the ability to: meet their basic needs; learn, grow, and make decisions; move around; build and maintain relationships, and contribute to society (Beard et al., 2016). Although there is no absolute consensus regarding the definition of healthy aging, the scientific community has tried to identify the factors that enable individuals to age physically and mentally healthily. In fact, there are several modifiable factors including physical activity (PA), smoking, and alcohol use, which can contribute to the increase of the likelihood of healthy aging, reduce premature death, prevent morbidity and disability, and improve the quality of life and well-being (Daskalopoulou et al., 2017). Thus, successful aging is associated with a healthy lifestyle, that promotes PA, preserves functional independence and quality of life, and reduces the risk of chronic diseases, including dementia (M. A. Gregory et al., 2013).

2. Physical activity

As defined by Caspersen and colleagues in 1985, PA is "any bodily movement produced by skeletal muscles that result in energy expenditure" (Caspersen, Powell, & Christenson, 1985). PA can be either classified as structured or incidental. Exercise is a subset of PA that is planned, structured, and repetitive, and is undertaken as a final or an intermediate objective of the improvement or maintenance of physical fitness and health. Incidental PA is not planned and is the result of daily activities at work, at home, or during transportation (Caspersen et al., 1985; Strath et al., 2013). Despite the differences, these terms are often confused and used interchangeably (Caspersen et al., 1985; Daskalopoulou et al., 2017).

2.1. Dimensions and domains of physical activity

PA is usually described by the following four dimensions: (i) frequency – the number of events of PA during a specific time; (ii) duration – the time of participation in a single bout of PA; (iii) intensity – the physiological effort associated with participating in a special type of PA; and (iv) type of activity (Strath et al., 2013; Warren et al., 2010). Ideally, the assessment of PA should measure all these dimensions and account for day-to-day variations. Three of these dimensions (i.e., intensity, frequency, and duration) are fundamental because their assessment allows the calculation of the energy expenditure (EE) associated with PA (Warren et al., 2010). In addition, the domains in which PA occurs are essential to understand the PA assessment. The domains of activity are usually defined as the household or domestic, the occupational, the transportation, and the leisure time (Strath et al., 2013; Warren et al., 2010). Therefore, the assessment of total PA should capture each of the 4 domains, otherwise, it will be incomplete (Strath et al., 2013).

2.2. Classification of physical activity intensity

PA intensity is usually classified as light, moderate, or vigorous intensity, depending on the effort or amount of energy expended by an individual during the activity (Aparicio-Ugarriza et al., 2015; Khoja, Almeida, Chester Wasko, Terhorst, & Piva, 2016). According to Ainsworth classification, light intensity activities require the least amount of effort and are defined as < 3 METs (metabolic equivalent of task) (Ainsworth et al., 2000). MET is the ratio of a person's working metabolic rate relative to their resting metabolic rate. Light physical activities include activities such as walking slowly, sitting, eating, preparing food, and washing dishes (Ainsworth et al., 2000; Cristi-Montero, 2017). Moderate-intensity activities are defined as activities ranging between 3 and 6 METs. These activities require more oxygen consumption than light activities. Examples of moderate physical activities include sweeping the floor, walking briskly, slow dancing, washing windows (Ainsworth et al., 2000). Vigorous activities require the highest amount of oxygen consumption to complete the activity and are defined as ≥ 6 METS. These activities include running, swimming, shoveling, soccer, carrying heavy loads (Ainsworth et al., 2000). Additionally, sedentary behavior is defined by the Sedentary Behavior Research Network as any waking behavior characterized by an energy expenditure of ≤ 1.5 METs in a sitting or reclining posture (Cristi-Montero, 2017). Finally, these values of cut-point-based of PA and sedentary behavior have important implications for the time estimates of activity (Aparicio-Ugarriza et al., 2015).

3. Physical activity and healthy aging

Regular PA is essential for healthy aging and chronic disease prevention, with benefits on health and overall quality of life in older adults well established (Daskalopoulou et al., 2017; Lee, Jackson, & Richardson, 2017; Lohne-Seiler, Hansen, Kolle, & Anderssen, 2014). Clinical and epidemiological studies suggest that PA reduces the risk of chronic diseases, such as cardiovascular disease, stroke, obesity, type II diabetes, and hypertension (Daskalopoulou et al., 2017; Kononova et al., 2019; Lyons, Swartz, Lewis, Martinez, & Jennings, 2017; Mercer et al., 2016). It has also been associated with improved cognition and mental health (Chieffi et al., 2017; Daskalopoulou et al., 2017; Kononova et al., 2019; Steinert, Haesner, & Steinhagen-Thiessen, 2018), preventing frailty and falls, and contributing to a longer independent life (Kononova et al., 2019; Mercer et al., 2016). Furthermore, PA has been consistently associated with decreased all-cause mortality rates, probability of late survival (Daskalopoulou et al., 2017), improvements in the immune system, and reduced risk of infection (Di Liegro, Schiera, Proia, & Di Liegro, 2019). Additionally, a systematic review and meta-analysis from

Daskalopoulou (2017) highlight the positive impact of PA on the healthy aging process. In most of studies, the authors observed that when participants engaged in PA their odds of living a healthy life at an older age increased compared to participants that were physically less active or inactive (Daskalopoulou et al., 2017).

Over recent years PA has attracted growing interest as a strategy to delay the effects of both physiological aging and pathological neurodegeneration on brain health (Barnes, 2015; Di Liegro et al., 2019). Prospective and cross-sectional studies have shown that PA helps older adults to maintain optimal cognitive function throughout life and reduce the risk of cognitive impairment and dementia (Heyn, Hirsch, York, & Backus, 2016; Quigley, MacKay-Lyons, & Eskes, 2020). Moreover, emerging evidence from randomized controlled trials and meta-analyses suggests that exercise interventions can improve cognition, including executive function, cognitive flexibility, working memory, verbal fluency, and learning, in older adults (Quigley et al., 2020). Besides this, in 2011 a scientific statement from the American Heart Association concluded from a large-scale meta-analysis that PA protects against cognitive decline, revealing a complex interaction between vascular physiology and AD pathology (Gorelick et al., 2011). A review from Quigley et al. (2020) suggested four main biological mechanisms that appear to underlie exercise-induced cognitive improvement among older adults: upregulation of growth factors (brain-derived neurotrophic factor (BDNF), insulin-like growth factor-1 (IGF-1), and vascular endothelial growth factor (VEGF)) and neuroplasticity; inhibition of inflammatory biomarker production including the (C-reactive protein (CRP), interleukin (IL)-6 and -1 beta, and tumor necrosis factor alpha (TNF-alpha)); improved vascular function, and hypothalamic-pituitary-adrenal axis regulation (Quigley et al., 2020).

In addition, several neuroimaging studies also suggested a protective role of PA in preventing age-related decline related to brain atrophy and increase of gray matter and white matter of brain areas, including frontal, temporal lobes, and hippocampus. Notably, the brain regions that have more benefits are also those that seem more vulnerable to aging and are often reported to be severely affected in dementia (Chieffi et al., 2017; Domingos, Pêgo, & Santos, 2020). Furthermore, evidence from functional MRI studies showed greater task-relevant activity in brain areas recruited in executive function and memory tasks.

Conversely, physical inactivity has been associated with an unfavorable biomarker profile in older age (8). Moreover, physical inactivity is a growing problem worldwide, and it has been reported to cause 9% of all premature death (Larsen, Christensen, Juhl, Andersen, & Langberg, 2019). Despite this, studies have shown that PA can reverse at least some of the unwanted effects of a sedentary lifestyle, contributing to delaying brain aging and degenerative pathologies (23). In fact, sedentary older adults who become physically active show significantly less formation of beta-amyloid, which is a brain protein involved in the development of AD (Heyn et al., 2016). Therefore, PA may represent an accessible, effective, and low-cost therapeutic intervention to improve neurocognitive functions (Chieffi et al., 2017; M. A. Gregory et al., 2013).

Finally, guidelines proposed by the American College of Sports Medicine and the American Heart Association recommended a minimum of 150 minutes of PA with moderate-intensity or 75 minutes of vigorous-intensity or an equivalent combination of moderate and vigorous PA per week for older adults (Haskell et al., 2007; Nelson et al., 2007). Despite this recommendation, several studies have shown that PA levels and intensity often decline with age (Kononova et al., 2019; Lyons et al., 2017; Mercer et al., 2016).

4. Physical activity assessment

The assessment of PA in a free-living environment, a multidimensional and complex behavior, is difficult to measure. No single method can capture all PA domains. Inaccurate measures may have serious implications that could lead to inconsistent and false-negative results or underestimate effect size for the association between PA or sedentary behavior and health outcomes (Warren et al., 2010). Therefore, the evaluation of the dose-response relationship between PA and health is dependent on the accurate measurement of PA (Sylvia et al., 2014; Warren et al., 2010). It is essential both for epidemiological and clinical studies an objective, precise, and reliable method for the assessment of PA in free-living subjects (Sallis, 2010; Warren et al., 2010; Westerterp, 2009).

There are many techniques for PA assessment, which can be grouped into the following general categories: behavioral observation, questionnaires (including diaries, recall questionnaires, and interviews), and physiological markers such as heart rate, calorimetry, and motion sensors (LaPorte, Montoye, & Caspersen, 1985; Westerterp, 2009). No single instrument fulfills the criteria of being valid, reliable, and practical while not affecting behavior. The more precise instruments tend to be unfeasible in population-based studies. The questionnaires are the most practical approach in large-scale studies, even though little is known about their reliability and validity (LaPorte et al., 1985; Westerterp, 2009).

4.1. Subjective methods of assessing PA

Self-report instruments are the most widely used methods to assess PA and include self or interviewer-administered (face-to-face or by phone) questionnaires, recalls and activity diaries (Warren et al., 2010; Westerterp, 2009). The questionnaires are used to identify the dimensions and domains of PA from either self-reported responses or interviews. These instruments range from a few items, for a global overview of activity, to a long detailed quantitative history of activity over the past year or even a lifetime. There are 3 categories of PA questionnaires: global, recall, and quantitative history (Strath et al., 2013). The commonly used self-report questionnaires include the Baecke Physical Activity Questionnaire, the International Physical Activity Questionnaire, and Yale Physical Activity Survey (Warren et al., 2010). The strengths of self-report questionnaires include low cost of administration and is the cheapest and easiest way to collect PA data from many people in a short time. Furthermore, questionnaires also provide information on the type, and duration of PA (e.g., leisure, household, work, transportation) (Nicaise, Crespo, & Marshall, 2014). Nonetheless, there are several limitations including difficulties in determining the frequency, duration, and intensity of PA, capturing all PA domains, the tendency to over-report activity levels, social desirability bias, and the cognitive demands of recall (Sallis, 2010; Warren et al., 2010).

4.2. Objective methods of assessing PA

There are several methods available to objectively assess PA which include measures of energy expenditure, physiological measures, motion sensors, and methods that combine more than one type of sensors (Strath et al., 2013). Motion sensors that measure body motion can be used to assess PA and estimate energy expenditure. The most used are accelerometers and pedometers (Strath et al., 2013). Accelerometer sensors allow the measurement of the body's acceleration during the movement and provide information about the total amount, the frequency, the intensity, and the duration of PA (Strath et al., 2013; Westerterp, 2009). Data are collected in real-time which allows the determination of PA patterns (Warren et al., 2010). They can be used to assess sedentary time by counting minutes with very little movement. Moreover, these devices enable to determine whether participants are meeting moderate-to-vigorous PA guidelines (Sallis, 2010). Despite that, these sensors are not accurate in assessing upper body movement or cycling (Sallis, 2010; Warren et al., 2010). Additionally, they also underestimate the energy cost of walking on an incline or carrying heavy loads as the acceleration patterns remain essentially unchanged under these conditions, despite the increase in effort and the subsequent energy cost required (Warren et al., 2010). Notably, accelerometers are easy for participants to use but challenging for researchers due to the large volume of data generated that must be checked, cleaned, scored, and summarized. Furthermore, there is no consensus on how to define valid wearing days or how to score the data, and different "cut-points" are needed to define intensity levels for each age group (Sallis, 2010).

Pedometers are waistband-worn motion sensors that record steps (Craig et al., 2003; Strath et al., 2013). They are easy to use for participants and evaluators and accurately assess measure walking behavior. However, these devices are less useful for running, cycling, and water activities, and work less well for older adults who walk too slowly (Sallis, 2010).

Recently a few objective assessment devices provide multiple measurement parameters, such as heart rate monitoring combined with accelerometer measures (Strath et al., 2013; Warren et al., 2010). The combined motion sensor has improved accuracy in predicting energy expenditure. Although these monitors are relatively expensive, they are currently being used in semi large-scale population-based studies suggesting that they are a feasible option in epidemiological research (Warren et al., 2010).

Albeit objective monitors provide accurate information, they need resources and expertise to collect and manage the data (Sallis, 2010).

Concluding, due to the many choices available to assess PA in a free-living environment, selecting a method can be a challenging proposition.

5. Wearable technologies among older adults

Wearable tracking technologies, such as smartwatches and other wristband sensors, have shown that may increase PA levels, which is specifically beneficial for older adults due to its protective effect against age-related diseases (Campelo & Katz, 2020; Kononova et al., 2019; Schlomann, Seifert, & Rietz, 2019). Despite the benefits, digital care is more available in younger populations (Kononova et al., 2019), having limited use by the elderly (Preusse, Mitzner, Fausset, & Rogers, 2017). Indeed, in 2014 only 7% of older adults owned an activity tracker (Kononova et al., 2019). Possibly the seniors may not use wearable tracking technologies because of usability barriers (Preusse et al., 2017; Steinert et al., 2018).

Older adults may be more resistant to new technologies since they frequently have learning difficulties related to technical experience or skill, technology readiness, and education (Rupp, Michaelis, McConnell, & Smither, 2018; Scheid & West, 2019). The lack of familiarity is also an important reason for the non-use of PA tracking technologies (Seifert, Schlomann, Rietz, & Schelling, 2017). Furthermore, seniors may have anxiety and lower self-efficacy (Rupp et al., 2018). In fact, over 75% of the over-65 age group state that requiring assistance to use new technologies. The main reason for the need for technical assistance is because most technology systems are not developed for older users and frequently have small buttons, fiddly controls, complex interfaces, complex commands, and operating procedures (Steinert et al., 2018). Moreover, the colors, font sizes, and the display of critical information such as steps taken, and battery life that usually are hard for the elderly to interpret and are important aspects to consider to decreasing barriers and promote the usability and the acceptance of activity trackers (Preusse et al., 2017). In addition, factors associated with normal aging such as physical and cognitive decline could limit the ability to adopt the technology (Berkowsky, Sharit, & Czaja, 2018). Therefore, it is required a better understanding of the barriers and facilitators that older adults face when using technologies to understand whether they are satisfied or not. This is crucial to promote technology adoption and to ensure an appropriate implementation in clinical and research settings (Campelo & Katz, 2020; Farina & Lowry, 2017). Future research should consider design features of activity trackers before implementing them in older adults (Farina & Lowry, 2017).

Finally, in this work, we intend to broaden the knowledge of the association between PA (measured with a wearable device) and brain structure and function, and at the same time provide new insights regarding wearable technologies among older adults.

6. Aims

In this thesis, we performed an observational cross-sectional study in older individuals, using a multimodal imaging approach combined with an objective measurement of daily PA to explore brain health (structure and function) in aging populations. The study was divided into the following objectives:

- Compare accelerometer-based estimates of PA from Xiaomi Mi Band 2® with commonly used self-report questionnaires and assess PA profile in community-dwelling older adults.
- Evaluate the usability, feasibility, and performance of a wearable monitoring system (Xiaomi Mi Band 2®) in older populations.
- Explore associations between PA and brain structure and function by objectively evaluating PA and conducting parallel neuroimaging studies.

7. Chapters overview

This thesis is organized into five chapters.

In **Chapter I**, we aimed to compare accelerometer-based estimates of PA from Xiaomi Mi Band 2® with PA data obtained from self-report questionnaires in older adults.

In **Chapter II**, we conducted a transcultural adaptation and validation of a questionnaire to evaluate user satisfaction with technologies in Portuguese older adults.

In **Chapter III**, we investigated the acceptability, usability, and user satisfaction of an activity tracker (Xiaomi Mi Band 2®) in Portuguese community-dwelling older adults.

In **Chapter IV,** we systematically reviewed the literature exploring cross-sectional and longitudinal neuroimaging MRI studies that have examined the relationship between PA and brain structure and function in older adults without cognitive or neuropathological disease.

In **Chapter V**, we explored the associations between PA and brain structure and function by objectively evaluating PA and conducting parallel neuroimaging studies.

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CHAPTER I

Association between self-reported and accelerometer-based estimates of physical activity in Portuguese older adults

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Association between self-reported and accelerometer-based estimates of physical activity in Portuguese older adults

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1. Abstract

Accurate assessment of physical activity (PA) is crucial in interventions promoting it and in studies exploring its association with health status. Currently, there is a wide range of assessment tools available, including subjective and objective measures. This study compared accelerometer-based estimates of PA with self-report PA data in older adults. Additionally, the associations between PA and health outcomes and PA profiles were analyzed. Participants (n = 110) wore a Xiaomi Mi Band 2® for fifteen consecutive days. Self-reported PA was assessed using the International Physical Activity Questionnaire (IPAQ) and the Yale Physical Activity Survey (YPAS). The Spearman correlation coefficient was used to compare self-reported and accelerometer-measured PA and associations between PA and health. Bland–Altman plots were performed to assess the agreement between methods. Results highlight a large variation between self-reported and Xiaomi Mi Band 2® estimates, with poor general agreement. The highest difference was found for sedentary time. Low positive correlations were observed for IPAQ estimates (sedentary, vigorous, and total PA) and moderate for YPAS vigorous estimates. Finally, self-reported and objectively measured PA associated differently with health outcomes. Summarily, although accelerometry has the advantage of being an accurate method, self-report questionnaires could provide valuable information about the context of the activity.

Keywords: seniors; elderly; physical activity; accelerometry; fitness trackers; self-report physical activity; IPAQ; YPAS

2. Introduction

Regular physical activity (PA) is essential for healthy aging and chronic disease prevention, with its benefits on general health and overall quality of life in older adults being well established (Lee, Jackson, & Richardson, 2017; Lohne-Seiler, Hansen, Kolle, & Anderssen, 2014). Specifically, PA contributes to maintaining physical function and performance (e.g., walking speed, handgrip strength) (Langhammer, Bergland, & Rydwik, 2018) and plays a preventing role in frailty and falls (Kononova et al., 2019; Mercer et al., 2016). Furthermore, it associates with more favorable body composition and anthropometric parameters such as body mass index (BMI), waist circumference, and weight (Dunsky et al., 2014). There is also increasing evidence of its beneficial effects on various neuropsychological outputs (Busse, Gil, Santarém, & Jacob Filho, 2009). Despite this, the quantification of the strength and nature of the relationship between PA and health outcomes should rely on the accurate measurement of PA behavior (Celis-Morales et al., 2012).

In population-based studies, there are currently several objective and subjective self-report instruments available (Oyeyemi, Umar, Oguche, Aliyu, & Oyeyemi, 2014), but with accumulating scientific evidence being mainly based on the latter (e.g., self-report questionnaires, logs, recalls, and activity diaries) (Haskell, 2012; Lohne-Seiler et al., 2014). Nonetheless, recalling PA is a complex cognitive task, particularly for older adults who may have memory and recall limitations (Lohne-Seiler et al., 2014). Indeed, self-report questionnaires have limited validity in measuring daily activities due to issues with question interpretation, imprecise recall, judgment formation, and response editing (Celis-Morales et al., 2012; Kirk I. Erickson et al., 2014; Nicaise et al., 2014). On the other hand, self-report measures are more feasible for use in large-scale studies because of their low cost and ease of use (Celis-Morales et al., 2012; Nicaise, Crespo, & Marshall, 2014; Oyeyemi et al., 2014; Rääsk et al., 2017; Schmidt et al., 2020). Moreover, questionnaires can provide information on the type (e.g., leisure, household, work, transportation) and duration of PA (e.g., $min.day^{-1}$, $min.wk^{-1}$, $h.wk^{-1}$) (Nicaise et al., 2014). Still, and complementing this type of methodology, more objective PA measurement is of concern. Across time and populations, accelerometers are reliable and valid objective instruments (Kirk I. Erickson et al., 2014; Lohne-Seiler et al., 2014; Schwenk et al., 2015), providing a precise assessment of everyday activities (frequency, duration, intensity, and type), and allowing for the identification of specific PA patterns (Kirk I. Erickson et al., 2014; O'Neill et al., 2017; Schwenk et al., 2015), without the need for self-report (Erickson, Leckie, & Weinstein, 2014). However, they are unable to capture all PA dimensions, such as leisure, household, work, and transportation activities (Nicaise et al., 2014).

Previous studies using both measurement types have observed some differences in the obtained PA estimates (Oyeyemi et al., 2014). In general, self-report measures both underestimate sedentary time (Stephanie A. Prince et al., 2020) and overestimate PA levels when compared to PA objective measures (Dyrstad, Hansen, Holme, & Anderssen, 2014; Hagstromer, Ainsworth, Oja, & Sjostrom, 2010; Stéphanie A. Prince et al., 2008; Stephanie A. Prince et al., 2020). Furthermore, research conducted on the general population has suggested self-reported measures of PA as inaccurate and showing a weak to modest correspondence when compared with objective measures (Boyle, Lynch, Courneya, & Vallance, 2015; Rääsk et al., 2017; Schmidt et al., 2020). Therefore, one of the challenges is to select the most accurate and practical tool with a balance between precision and feasibility (Celis-Morales et al., 2012), both in research and in clinics. Notably, poor methods increase the chances of misclassification and can mask or distort the true underlying relationship between PA and health outcomes (Celis-Morales et al., 2012). This can be particularly notable in what regards accelerometer and self-report measures in sedentary behavior (Stephanie A. Prince et al., 2020). Additionally, there is a lack of knowledge about the PA levels and sedentary behavior among the elderly (Lohne-Seiler et al., 2014) and, despite all the evidence supporting their benefits in health outcomes, there is a need to clarify the strength of this relationship. Thus, comparison studies between accelerometry and self-report methods are essential.

In a sample of community-dwelling of Portuguese older adults in Northern Portugal, here the study objectives were to (i) compare PA assessed by commonly used self-report questionnaires versus objective PA assessed by accelerometry, and (ii) describe the levels of PA and explore their associations with body composition and physical function. Results may provide further insight on accelerometer measurements and PA levels and sedentary behavior in the senior population, contributing to the future implementation of this wearable technology in clinical and research settings.

3. Methods

Ethics Statement

The study was approved by the local ethical committees (Approval Number 42-2018), conducted in accordance with the Declaration of Helsinki (59th Amendment), developed in compliance with the new General Data Protection Regulation, and approved by the Portuguese Data Protection Authority (Approval Number 11286/2017). The study goals and assessments were explained to participants during screening procedures. Written informed consent was obtained from all participants prior to the study enrollment.

Participants

A convenience sample of 120 community-dwelling older adults were recruited from local health centers and gyms from the municipality of Braga in Northern Portugal. The eligible criteria were: (1) men and women between 64 to 75 years of age; (2) ability to understand the informed consent; (3) ability to attend the assessment sessions; (4) ability to wear Xiaomi Mi Band 2® for fifteen consecutive days; (5) free of diagnosed neurological or psychiatric diseases; (6) adequate visual, auditory, and fine motor skills; and (7) not having any disability that limited independent walking. From the enrolled sample, 110 participants completed all assessment sessions.

Data collection

The study had a cross-sectional study design. A baseline characterization was performed encompassing: (1) a structured questionnaire-based interview to assess socio-demographic and clinical information; (2) a neuropsychological evaluation to characterize depressive mood (Geriatric Depression Scale, GDS) (Jerome A Yesavage et al., 1982) and global cognitive profiles (Mini-Mental State Examination, MMSE) Guerreiro et al., 1994); (3) an anthropometric and body composition evaluation; and (4) physical performance evaluation (Figure 1). Lastly, self-reported PA was assessed with the International Physical Activity Questionnaire (IPAQ), long version (Craig et al., 2003), and The Yale Physical Activity Survey for older adults (YPAS) (Machado et al., 2016) through personal interviews. The Xiaomi Mi Band 2® was used to objectively assess PA levels.

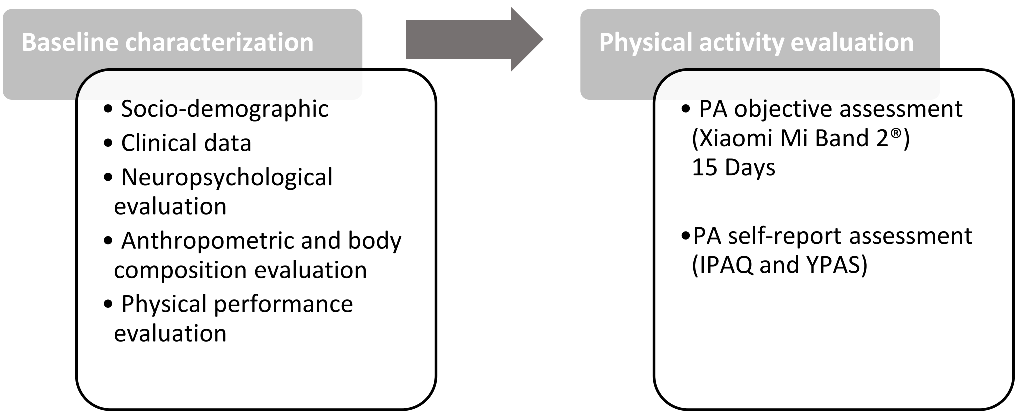

Figure 1. Flow diagram of the assessments.

Neuropsychological Evaluation

The MMSE is the most used instrument for screening cognitive impairment. The Portuguese transcultural adaptation, standardization, and validity were carried out by Guerreiro et al. (1994) (Guerreiro et al., 1994). Cognitive performance was classified according to the MMSE Portuguese version, the cut-off scores for “cognitive impairment” are as follows: individuals with no education, <15 points; 1 to 11 years of school completed, <22 points; and >11 years of school completed, <27 points (Santana et al., 2016). The GDS was designed for rating depression in the elderly by Yesavage et al. (1983) (Jerome A. Yesavage et al., 1982). GDS appears to be a valid and reliable test for use in depression screening in Portuguese elders Scores range from 0 to 30, with values >11 indicating the presence of depressive symptomatology (Pocinho, Farate, Dias, Lee, & Yesavage, 2009).

Anthropometric characterization

The anthropometric measures included weight (Tanita BF 350 Body Composition Analyzer), height (Seca 217 Stadiometer), and waist (WC), and hip circumferences (HP) (ergonomic measuring tape). Body mass index (BMI) was calculated as weight (kg)/height (m2). BMI was categorized as underweight, normal, overweight, and obese (respectively, BMI: 0–18.5, 18.6–24.9, 25.0–29.9, and 30.0+). The waist-to-hip ratio (WHR) was obtained by dividing the WC (cm) by HP (cm) circumference. WHR above 0.90 for males and above 0.85 for females was categorized as a substantially increased risk of metabolic complications (World Health Organization, 2011).

Body composition

Body composition was estimated by bioelectrical impedance analysis using a Maltron BioScan 920-II Multi-frequency Analyzer. The measurements were conducted according to manufacturer instructions. The cut-off values for body fat (FAT) percentage are ≤42% for women and ≤30% for men (Pérez-Ros, Vila-Candel, López-Hernández, & Martínez-Arnau, 2020).

Physical performance

Measurements of physical performance included gait speed (6-m walking test) and handgrip strength (Jamar Hand Dynamometer). Slow gait speed was classified as walking less than 1 m/s, which is the predictive value that identifies persons at high risk of health-related outcomes in well-functioning older people (Cesari et al., 2005). For handgrip strength the normative data ranging from 22.5 to 25.6 kg for women and 36.2 to 41.7 kg for men (Beaudart et al., 2019). Functional status was assessed using the Lawton Instrumental Activities of Daily Living (IADL) scale to assess independent living skills (Lawton & Brody, 1969), Katz Activities of Daily Living (ADL) scale to assess six primary and psychosocial functions (bathing, dressing, going to the toilet, transferring, feeding, and continence) (Katz, Ford, Moskowitz, Jackson, & Jaffe, 1963), and Tinetti-test to assess the gait and balance (Tinetti, 1986).

International Physical Activity Questionnaire (IPAQ)

The IPAQ is the most widely used tool to collect self-reported PA. It was developed as an instrument for standardizing measures of the health-related PA behaviors of the population in multiple countries and different sociocultural contexts. Moreover, the validity and reliability of the IPAQ has been established in a 12-country evaluation, including Portugal (Craig et al., 2003). The long-form of IPAQ comprises 27 items measuring the frequency and duration of PA performed in four domains, including occupational, transportation, household/gardening, and leisure-time activities, as well as sedentary activities, in the last seven days. The questionnaire was designed to provide separate domain-specific scores for walking, moderate-intensity, and vigorous-intensity activity, within each of the domains. The total score is estimated by summing all domains and intensity-specific PA minutes weighted by their metabolic equivalents (METs) and expressed in MET-minutes per week. According to the IPAQ scoring protocol, vigorous-intensity PA is defined as 8 METs, moderate-intensity activity 4 METs, and walking 3.3 METs (Craig et al., 2003; IPAQ Research Committee, 2005). The data collected in this study were analyzed following the IPAQ scoring protocol (Craig et al., 2003; IPAQ Research Committee, 2005).

Yale Physical Activity Survey (YPAS)

The YPAS is an interviewer-administered questionnaire developed to assess PA in epidemiologic studies of community-dwelling older adults. The YPAS-PT version demonstrates acceptable validity and reliability to measure PA levels in the Portuguese older adults (Machado et al., 2016). The questionnaire is divided into two sections allowing the estimation of PA in a typical week in the last month before evaluation. The first section comprises a detailed checklist about the type, duration, and intensity of 25 activities in five domains: household, yard work, caregiving, exercise, and recreational activities. The weekly PA energy expenditure (EE) is calculated by multiplying the total time spent in each activity by an intensity code (kcal.min^{-1}) and then summed across all activities to create a weekly value (kcal.wk^{-1}). The second section contains questions that estimate the frequency and duration in five distinct PA dimensions: vigorous activity, leisurely walking, moving, standing, and sitting. The index for each dimension is calculated by multiplying the frequency score by duration score and multiplying again by a weighting factor. A summary index of activity is the sum of the five individual indices. The weights are based on the intensity of the activity dimension (Dipietro, Caspersen, Ostfeld, & Nadel, 1993; Harada, Chiu, King, & Stewart, 2001; Machado et al., 2016).

Xiaomi Mi Band 2®

Participants were instructed to wear the wrist accelerometer continuously for fifteen consecutive days while performing their normal daily activities. The Master for Mi Band app was used to export data (steps and heart rate) in SQLite format then converted to CSV format.

Xiaomi Mi Band 2® (15.7 mm × 10.5 mm × 40.3 mm and weighs 7.0 g) was selected among several commercially available wearable activity trackers because it has an estimated battery life of almost 30 days, is ergonomic, accessible, easy to operate, and offers a good price-quality ratio. The system combines sensors that allow the objective assessment of daily free-living PA, sleep, and heart rate (El-Amrawy & Nounou, 2015; Mičková, Machová, Daďová, & Svobodová, 2019; Puri et al., 2017; Xie et al., 2018). Specifically, it has a triaxial accelerometer to detect movements, photoplethysmography sensor to monitor blood-volume changes, and combines a proximity sensor with actigraphy to detect sleep (Mičková et al., 2019). The algorithms used by the system are reliable to measure steps, intensity, energy expenditure, and distance traveled (El-Amrawy & Nounou, 2015; Mičková et al., 2019; Puri et al., 2017; Xie et al., 2018). Moreover, Xiaomi Mi Band 2® was tested for accuracy, precision, and validity. El-Amrawy has demonstrated that its high measurement accuracy (96.56%) and the relatively low variation coefficient (CV = 5.81) (El-Amrawy & Nounou, 2015). Furthermore, other authors also indicated a good accuracy and precision for this system (El-Amrawy & Nounou, 2015; Xie et al., 2018).

Data reduction

Data reduction and cleaning were performed using Microsoft Excel. From the 15 days of wear time, seven consecutive valid days were collected. The first day of recording was not included in the analysis. Data were included in the analysis if the participants had a minimum of 5 valid days, including at least one weekend day (Nicaise et al., 2014; O'Neill et al., 2017). A valid day was defined as at least 10 h of records per day, and non-wear time as more than 30 consecutive minutes with zero activity (Ferrari et al., 2020; Troiano et al., 2008). The following PA intensity-specific cut-points were applied to the raw data: sedentary 0–19 steps/min; light intensity 60–99 steps/min, moderate activity 100–119 steps/min, and vigorous-intensity ≥120 steps/min C. Tudor-Locke et al., 2011; Catrine Tudor-Locke et al., 2018). Additionally, the older adults were classified using the following graduated step index: sedentary <5000 steps/day; low active 5000–7499 steps/day; somewhat active 7500–9999 steps/day active ≥10,000–12,499 steps/day; and highly active ≥12,500 steps/day (C. Tudor-Locke & Bassett, 2004; Catrine Tudor-Locke et al., 2011).

Statistical analysis

Data were analyzed using IBM SPSS Statistics (version 26). Descriptive statistics for continuous data are presented as mean ± standard deviation (SD). Categorical data are presented as absolute values and percentages. Normal data distribution was examined using the Shapiro–Wilk test, skewness, kurtosis, and histograms. Absolute values for skewness above 2.0 and kurtosis above 4.0 were considered as reference values for determining normality. Shapiro–Wilk test was used to validate the normality of all variables. A p-value below 0.05 indicates that the data significantly deviate from a normal distribution (Mishra et al., 2019).

Gender differences on PA levels, anthropometric, body composition, and physical performance measures were assessed using independent sample t-test or Mann–Whitney U, depending on the normality of the variables. A p-value of less than 0.05 was considered statistically significant.

One sample T-test for the differences between accelerometer–measured and self-reported PA was used to determine if there is an agreement between the measurements. Furthermore, visual inspection of the Bland–Altman plot was used to explore the strength of agreement between the methods (Altman & Bland, 1983) and linear regression to determine if there is a proportional bias. Variables used for the Bland–Altman analysis were sedentary time, moderate, and vigorous PA, as well as total PA, according to IPAQ, YPAS, and Xiaomi Mi Band 2®.

Pearson or Spearman correlations were used to assess associations between accelerometer–measured PA, self-reported methods, and associations with health outcomes. The correlation coefficient was analyzed considering the Rule of Thumb (Hinkle, Wiersma, & Jurs, 2003).

Lastly, two-step cluster analysis was used to identify similar patterns of PA and sedentary behavior and association with health outcomes. Moderate PA, sedentary behavior, and meeting PA recommendations were clustering variables. Additionally, GDS, speed, BMI, and free fat mass (FFM) were included as evaluation fields. To establish how clusters that are statistically significant differed from one another, variables were examined using the Kruskal-Wallis H test.

4. Results

Study Participants

Table 1 summarizes the participants' demographic, depressive mood, global cognitive, anthropometric, body composition, and physical performance characteristics. The mean age was 68.4 (SD ± 3.1), 60% were female, and the mean number of years of formal education was 8.0 (SD ± 5.4) (number of school years).

Table 1. General characteristics of the study participants.

Characteristics	Total Sample *n* = 110	Male *n* = 50	Female *n* = 60	*p*-Value
Gender, *n* (%)		50 (45.5)	60 (54.5)	
Age, years (mean ± SD)	68.4 ± 3.1	69.4 ± 2,9	67.5 ± 3.0	<0.000
Education, years (mean ± SD)	8.0 ± 5.4	9.4 ± 6.0	6.8 ± 4.6	0.008
MMSE, total score (mean ± SD)	27.0 ± 2.0	27.1 ± 1.8	26.8 ± 2.1	0.57
GDS, total score (mean ± SD)	6.1 ± 4.6	5.3 ± 3.9	6.7 ± 5.0	0.25
Anthropometric (mean ± SD)				
Weight, Kg	73.6 ± 13.0	79.0 ± 11.8	69.2 ± 12.4	<0.000
Height, m^2	159.7 ± 8.36	166.3 ± 6.4	154.2 ± 5.3	<0.000
BMI, kg/m^2	28.5 ± 4.3	27.8 ± 3.5	29.0 ± 4.9	0.65
WC, cm	99.4 ± 9.8	100.2 ± 9.7	98.7 ± 9.7	0.43
HP, cm	104.8 ± 9.03	103.3 ± 6.9	106.0 ± 10.4	0.29
WHR	0.95 ± 0.07	0.97 ± 0.08	0.93 ± 0.06	0.013
Body composition (mean ± SD)				
FAT, %	33.5 ± 7.8	27.8 ± 5.2	38.3 ± 6.3	<0.000
FAT, Kg	24.7 ± 8.6	21.5 ± 6.5	27.3 ± 9.2	<0.000

FFM, %	66.5 ± 7.8	72.2 ± 5.2	61.7 ± 6.3	<0.000
FFM, Kg	48.2 ± 9.2	54.8 ± 7.6	42.7 ± 6.4	<0.000
Mineral, Kg	4.0 ± 0.5	4.2 ± 0.5	3.8 ± 0.4	<0.000
Muscle, Kg	23.7 ± 4.2	26.5 ± 3.6	21.3 ± 3.0	<0.000
BCM, Kg	27.5 ± 4.9	30.9 ± 4.2	24.7 ± 3.4	<0.000
Malnutrition Index	0.66 ± 0.05	0.69 ± 0.05	0.64 ± 0.04	<0.000
Physical performance (mean ± SD)				
ADL score	5.7 ± 0.5	5.9 ± 0.4	5.5 ± 0.6	0.002
IADL score	8.0 ± 0.1	8.0 ± 0.1	7.9 ± 0.2	0.67
Balance score	15.6 ± 0.7	15.5 ± 0.7	15.6 ± 0.8	0.28
Gait score	12.0 ± 0.2	12.0 ± 0.1	12.0 ± 0.1	0.1
Max Right Grip, Kg	31.0 ± 10.1	39.4 ± 8.0	24.0 ± 4.8	<0.000
Max Left Grip, Kg	29.6 ± 9.6	37.2 ± 8.6	23. ± 4.4	<0.000
Speed, m/sec	1.7 ± 0.3	1.8 ± 0.3	1.6 ± 0.3	<0.000

Abbreviations: MMSE, Mini Mental State Examination; GDS, Geriatric Depression Scale; BMI, Body mass index; WC, waist circumference; HP, hip circumference; WHR, waist-to-hip ratio; FAT, Fat Mass; FFM, Free Fat Mass; Muscle, Muscle mass; Mineral, Mineral body density; BCM, Body Cell Mass; ADL, Activities of Daily Living; IADL, Instrumental Activities of Daily Living.

According to cut-offs of the Portuguese version of MMSE all participants were classified as without cognitive impairment (27.0 ± 2.0). The GDS results indicated no presence of depressive symptoms (6.1 ± 4.6). The average BMI was 28.5 (SD ± 4.3), which is categorized as overweight, and the WHR ratio was 0.95 (SD ± 0.07), meaning that this sample of older adults had a substantially increased risk of metabolic complications. Results did not show statistical differences between genders for BMI or WHR. Women had significantly higher fat mass (%) 38.3 (SD ± 6.3) compared to men 27.8 (SD ± 5.2). The values are categorized within optimal values for both genders. The gait speed and handgrip strength were in the range of reference values, indicating good physical performance. The functional status evaluation confirmed the independence in activities of daily living and performance of instrumental activities of daily living.

The descriptive data from IPAQ, YPAS, and Xiaomi Mi Band 2® are presented in Table 2, Table 3, and Table 4, respectively. Overall, the activities self-reported were predominantly walking, household, leisure, and gardening activities. Furthermore, the results have shown a significant difference in PA measured by IPAQ between gender for domestic activities, sitting time, moderate activities, and total PA (Table 2), with higher values for women. Similarly, results from PA measured by YPAS also showed significant differences in domestic activities and total PA (Table 3).

Table 2. Descriptive PA data from International Physical Activity Questionnaire.

Variable	Total Sample *n* = 110	Male *n* = 50	Female *n* = 60	*p*-Value
Total Work (min.d^{-1})	218.4 ± 1272.8	209.6 ± 1201.7	225.7 ±1339.2	0.53
Total Transport (min.d^{-1})	698.5 ± 1013.0	903.5 ± 1107.2	527.7 ± 901.5	0.030
Total Domestic (min.d^{-1})	3789.9 ± 3948.5	1976.6 ± 3074.9	5301.0 ± 3980.2	<0.000
Total Leisure (min.d^{-1})	1248.6 ± 1577.4	1212.1 ± 1343.5	1279.0 ± 1759.4	0.99
Total Average Sitting (min.d^{-1})	247.4 ± 127.3	288.4 ± 149.0	213.4 ± 94.4	0.008
Total Walking (min.d^{-1})	1262.9 ± 1752.6	1313.4 ± 1292.3	1220.7 ± 2069.7	0.084
Total Vigorous (MET.min.d^{-1})	333.3 ± 828.4	432.7 ± 921.4	250.3 ± 739.8	0.22
Total Moderate (MET.min.d^{-1})	4359.3 ± 3884.9	2555.6 ± 3176.1	5862.3± 3801.4	<0.000
Total MET (MET.min.d^{-1})	5955.4 ± 3957.1	4301.8 ± 3380.0	7333.4 ± 3897.6	<0.000

Abbreviations: PA, physical activity; min.d^{-1}; minutes per day, MET.min.d^{-1}, metabolic equivalent of task minutes per day.

Table 3. Descriptive PA data from Yale Physical Activity Survey.

Variable	Total Sample $n = 110$	Male $n = 50$	Female $n = 60$	p-Value
Household Total Time (min.wk^{-1})	1022.4 ± 805.5	476.6 ± 520.4	1477.2 ± 714.8	<0.000
Household Total EE (kcal.wk^{-1})	3097.9 ± 2406.4	1542.7 ± 1566.8	4394.0 ± 2214.0	<0.000
Yard work Total Time (min.wk^{-1})	209.7 ± 514.4	137.6 ± 253.4	269.8 ± 653.8	0.71
Yard work Total EE (kcal.wk^{-1})	965.6 ± 2338.9	637.6 ± 1172.4	1238.9 ± 2966.1	0.71
Caregiving Total Time (min.wk^{-1})	124.4 ± 396.6	118.8 ± 279.5	129.0 ± 432.9	0.54
Caregiving Total EE (kcal.wk^{-1})	578.1 ± 1645.8	566.1 ± 1382.3	588.0 ± 1848.6	0.54
Exercise Total Time (min.wk^{-1})	218.2 ± 230.0	216.9 ± 234.2	219.3 ± 228.4	0.88
Exercise Total EE (kcal.wk^{-1})	1268.1 ± 1510.8	1217.7 ± 1327.4	1310.0 ± 1658.2	0.90
Leisure Total Time (min.wk^{-1})	117.9 ± 252.0	136.3 ± 299.1	102.6 ± 206.1	0.99
Leisure Total EE (kcal.wk^{-1})	388.8 ± 859.9	512.8 ± 1144.6	285.5 ± 504.1	0.87
Total PA Time (min.wk^{-1})	1692.6 ± 1107.0	1086.2 ± 821.4	2197.9 ± 1064.0	<0.000
Total EE (kcal.wk^{-1})	6298.4 ± 4152.3	4476.8 ± 3265.3	7816.4 ± 4224.1	<0.000
Vigorous activity index (units.month^{-1})	4.7 ± 13.1	7.5 ± 17.1	2.3 ± 7.9	0.16
Leisurely walking index (units.month^{-1})	14.6 ± 14.8	15.7 ± 14.3	13.7 ± 15.3	0.33
Moving index (h.d^{-1})	12.1 ± 3.7	11.0 ± 3.6	13.0 ± 3.5	0.003
Standing index (h.d^{-1})	1.0 ± 1.3	1.1 ± 1.4	1.0 ± 1.3	0.81
Sitting index (h.d^{-1})	1.8 ± 0.7	1.9 ± 0.7	1.6 ± 0.6	0.015
Stair climbing (units.d^{-1})	9.5 ± 12.5	9.9 ± 14.2	9.1 ± 11.0	0.78
Summary index (total units)	34.1 ± 20.4	37.2 ± 23.7	31.6 ± 16.9	0.42
Seasonal Adjust	1.2 ± 2.0	1.4 ± 3.0	1.00 ± 0.10	0.76

Abbreviations: PA, physical activity; min.wk^{-1}, minutes per week; EE, energy expenditure; kcal.wk−1, kilocalorie per week; h.d^{-1}, hours per day.

Table 4. Descriptive PA data from Xiaomi Mi Band 2®.

Variable	Total Sample $n = 110$	Male $n = 50$	Female $n = 60$	p-Value
Sedentary time (min.wk⁻¹)	9088.9 ± 735.7	9084.6 ± 639.0	9092.5 ± 813.0	0.33
Light PA (min.wk⁻¹)	275.4 ± 392.7	278.4 ± 316.3	272.9 ± 449.2	0.045
Moderate PA (min.wk⁻¹)	120.5 ± 127.9	116.5 ± 91.4	123.8 ± 152.5	0.40
Vigorous PA (min.wk⁻¹)	62.4 ± 113.5	63.5 ± 132.6	61.4 ± 96.0	0.14
Total PA Time (min.wk⁻¹)	991.1 ± 735.7	995.4 ± 634.0	987.5 ± 813.0	0.33

Abbreviations: PA, physical activity; min.wk⁻¹.

Xiaomi Mi Band 2®-measured PA have shown that the participants spent more time in light or moderate activities (275.4 ± 392.7, 120.5 ± 127.9 min.wk⁻¹, respectively), compared to vigorous activities (62.4 ± 113.5 min.wk⁻¹) (Table 4). On the other hand, no significant differences were observed between men and women in total minutes per day spent in all PA intensities, as measured by the Xiaomi Mi Band 2®.

Correlation Between Self-Reported and Accelerometer-Based Estimates of PA

Correlations between Xiaomi Mi Band 2® and PA measured by IPAQ and are shown in Table 5. A significant low positive correlation was found for sedentary time, vigorous-intensity, and total PA. For moderate-intensity, the results indicate a negligible correlation between accelerometer and self-reported PA. Concerning the correlations between Xiaomi Mi Band 2® and PA measured by YPAS, a significant moderate positive correlation ($r = 0.42$, $p = 0.001$) for vigorous-intensity was found (Table 5).

Table 5. Spearman correlations between Xiaomi Mi Band 2® and self-reported PA (IPAQ and YPAS).

Variable	r	*p*-Value
International Physical Activity Questionnaire		
Sedentary time	0.38	<0.000
Moderate time	0.04	0.70
Vigorous time	0.30	0.002
Total PA time	0.27	0.004
Yale Physical Activity Survey		
Moderate time	0.003	0.97
Vigorous time	0.42	<0.000
Total PA time	0.23	0.017

Agreement Between Self-Reported and Accelerometer-Based Estimates of PA

Analyses comparing the concordance of values between the Xiaomi Mi Band 2® and IPAQ showed that older adults reported both less sedentary time and less vigorous-intensity time compared to the accelerometer measured data. Moreover, there was a significant difference between the two methods for all intensities, except for vigorous-intensity time; meaning that the two methods only agree on the estimation of vigorous-intensity time ($p = 0.60$) (Table 6). Regarding the concordance of absolute values between the Xiaomi Mi Band 2® and YPAS, we observed higher self-reported PA for all intensities tested. Additionally, we observed that the two methods are significantly different from one another ($p = 0.001$) (Table 6).

Table 6. Mean difference in minutes per week between Xiaomi Mi Band 2® and self-reported PA (IPAQ and YPAS).

Variable	Mean Difference ± SD	*p*-Value
	International Physical Activity Questionnaire	
Sedentary time	7357.8 ± 940.9	<0.000
Moderate time	−1191.1 ± 1176.7	<0.000
Vigorous time	9.1 ± 180.9	0.60
Total PA time	−767.9 ± 1234.4	<0.000
	Yale Physical Activity Survey	
Moderate time	−885.0 ± 869.0	<0.000
Vigorous time	−190.9 ± 247.2	<0.000
Total PA time	−701.5 ± 1076.6	<0.000

Note: Positive mean difference value: Xiaomi Mi Band 2® PA is higher than self-reported PA. Negative mean difference value: Xiaomi Mi Band 2® PA is lower than self-reported PA.

Since a possible agreement between vigorous-intensity time obtained from the Xiaomi Mi Band 2® and IPAQ was found, the Bland–Altman plot was used to explore the strength of this agreement. Figure 2 and Figure 3 show the differences between Xiaomi Mi Band 2®–measured PA and IPAQ plotted against the mean of the accelerometer and IPAQ for vigorous PA minutes per week. Overall, the mean difference was 9.1 ± 180.9 min.wk^{-1}, and the limits of agreement presented a higher variation, ranging from −345.4 to 363.6 min.wk^{-1}. The mean of the data lies considerably above 0, indicating that the Xiaomi Mi Band 2® estimates are consistently greater than IPAQ estimates. Moreover, the cluster of points showed a trend or error proportional to the size of the measure.

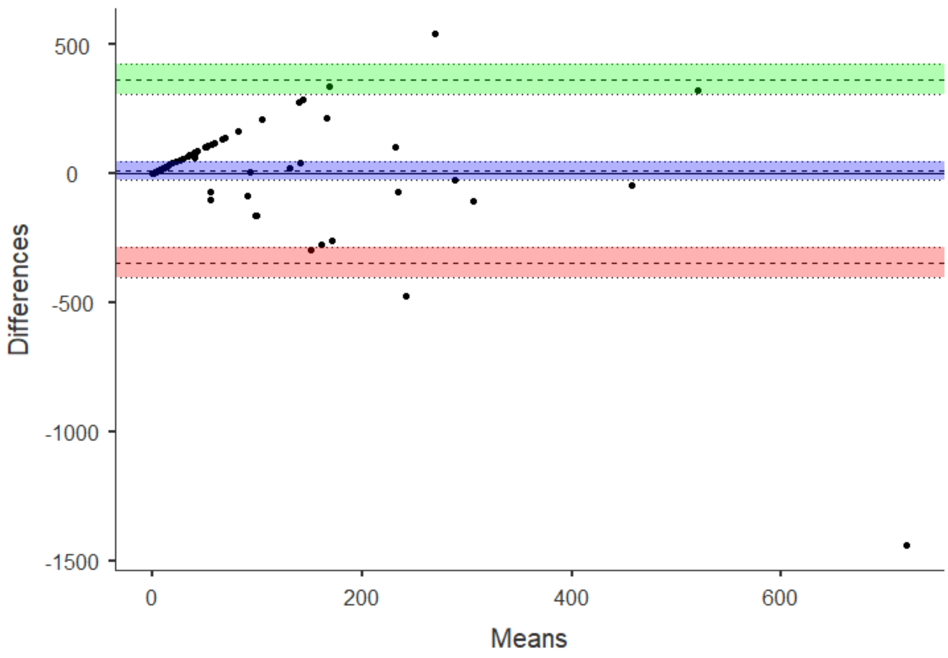

Figure 2. Bland–Altman plot for vigorous PA assessed by IPAQ and Xiaomi Mi Band 2®. The mean difference (systematic error) and 95% limits of agreement (mean ± 1.96 SD) and confidence interval shadings are displayed in the figure.

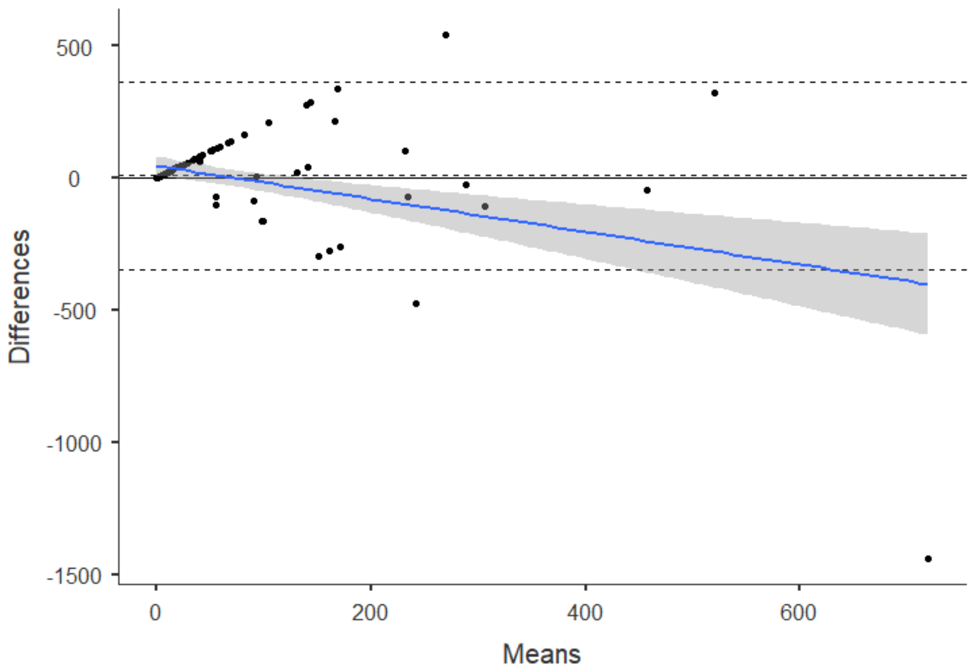

Figure 3. Bland–Altman plot for vigorous PA assessed by IPAQ and Xiaomi Mi Band 2®. The mean difference (systematic error) and 95% limits of agreement (mean ± 1.96 SD), proportional bias line, and proportional bias line confidence intervals are displayed in the figure.

Finally, the results from the regression analysis of the differences versus mean values confirms a significant systematic bias in the methods agreement ($p < 0.000$).

Association Between PA Estimates and Health Outcomes

The association between health outcomes variables with Xiaomi Mi Band 2®–measured and self-reported PA are presented in Table 7. IPAQ estimates show a moderate positive correlation with muscle mass and FFM, and a weak positive correlation with weight, WHR, and speed. Similarly, YPAS estimates also show a moderate positive correlation with muscle mass and FFM, and a weak positive correlation with weight. Concerning Xiaomi Mi Band 2®–measured PA, results reveal a weak positive correlation between a Xiaomi Mi Band 2®–measured PA and GDS, gait, and speed.

Table 7. Associations between Xiaomi Mi Band 2®–measured PA and the mean difference in minutes per week between Xiaomi Mi Band 2® and self-reported PA (IPAQ and YPAS) with health outcomes.

	Weight	WHR	BMI	FFM	Muscle	Education	GDS	Gait	Speed
				International Physical Activity Questionnaire					
r	−0.30	−0.24	−0.037	−0.39	−0.40	−0.092	−0.084	0.13	−0.22
***p*-value**	0.001	0.014	0.07	<0.000	<.000	0.339	0.382	0.182	0.020
				Yale Physical Activity Survey					
r	−0.30	−0.20	−0.007	−0.48	−0.48	−0.26	0.040	0.039	−0.19
***p*-value**	0.001	0.037	0.94	<0.000	<0.000	0.006	0.68	0.68	0.050
				Xiaomi Mi Band 2®					
r	−0.13	−0.071	−0.14	−0.010	−0.008	−0.076	−0.23	0.22	0.28
***p*-value**	0.19	0.47	0.14	0.92	0.94	0.43	0.017	0.022	0.003

Abbreviations: WHR, waist-to-hip ratio; BMI, Body mass index; FFM, Free Fat Mass; GDS, Geriatric Depression Scale.

Physical Activity Profile

Forty-eight percent of the participants (25.5% males and 22.7% females) were found to meet the guidelines of a minimum of 8000 steps/day (Table 8). In this sample of older adults, 45.5% had a sedentary behavior (17.3% sedentary, 28.2% low active) and 54.7% active behavior (25.5% somewhat active, 14.6% active, and 14.6% highly active).

Table 8. Classification of older individuals according to the current public health PA recommendations.

Characteristics	**Total Sample** *n* = 110	**Male** *n* = 50	**Female** *n* = 60
	Classification, *n* (%)		
Sedentary	19 (17.3)	7 (6.4)	12 (10.9)
Low active	31 (28.2)	13 (11.8)	18 (16.4)
Somewhat active	28 (25.5)	15 (13.6)	13 (11.8)
Active	16 (14.6)	8 (7.3)	8 (7.3)
Highly active	16 (14.6)	7 (6.4)	9 (8.2)
	PA recommendation, *n* (%)		
Meeting PA	53 (48.2)	28 (25.5)	25 (22.7)
Not meeting PA	57 (51.8)	22 (20.0)	35 (31.8)

Cluster Analysis of Physical Activity and Sedentary Behavior

The analysis revealed three distinct clusters with a silhouette measure of cohesion and separation of 0.8. Kruskal–Wallis H test confirmed that individual clusters differed significantly from each other. The different clusters showed the following consistent rank order of PA levels: C1 > C2 > C3. Cluster 1 displayed higher moderate PA levels, lower sedentary behavior, and meeting PA recommendations. In cluster 2, participants also met PA recommendations but had less moderate PA levels, and higher sedentary behavior, compared to cluster 1. On other hand, cluster 3 displayed low moderate PA levels, higher sedentary behavior, and participants did not meet the PA recommendations (Figure 4).

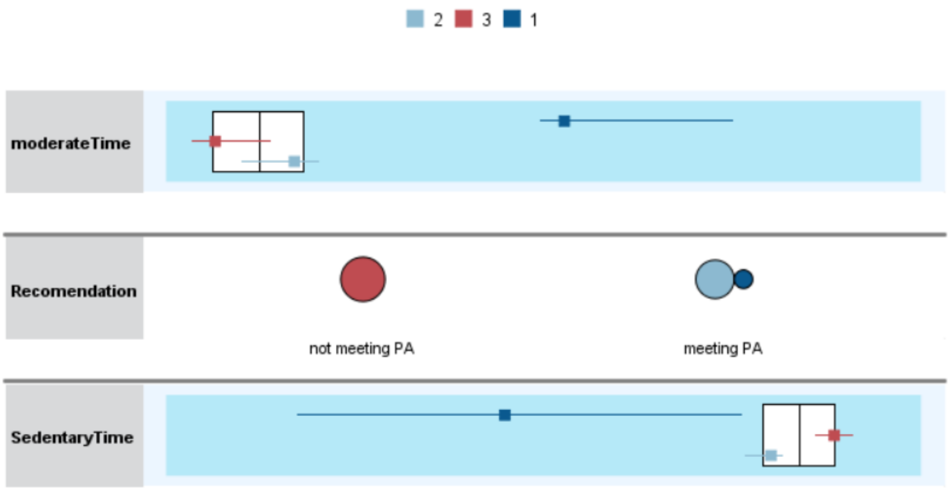

Figure 4. Cluster comparison.

Regarding the participant's characteristics within the clusters, GDS, speed, BMI, and FFM were significantly different, with better health-related outcomes in clusters that comprised the participants that meeting the PA recommendations (C1 and C2) (Table 9).

Table 9. Descriptive statistics for each cluster.

Characteristics	**C1** *n* = 10	**C2** *n* = 43	**C3** *n* = 57	***p*-Value**
PA recommendation, *n* (%)				
Meeting PA	10 (9)	43 (39)	0	
Not Meeting PA	0	0	57 (52)	
Sedentary time (mean ± SD)	7451.9 ± 1507.5	8998.8 ± 232.0	9444.1 ± 186.7	<0.000
Light PA (mean ± SD)	1091.8 ± 966.7	269.8 ± 100.9	136.4 ± 59.6	<0.000
Moderate PA (mean ± SD)	455.5 ± 154.4	119.2 ± 56.8	62.7 ± 46.3	<0.000
Vigorous PA (mean ± SD)	226.2 ± 236.3	88.5 ± 102.9	13.9 ± 21.3	<0.000
Total PA (mean ± SD)	2628.1 ± 1507.5	1081.2 ± 232.0	635.9 ± 186.7	<0.000
Speed (mean ± SD)	1.8 ± 0.3	1.8 ± 0.3	1.6 ± 0.3	<0.000
GDS (mean ± SD)	5.1 ± 3.5	4.6 ± 3.8	7.3 ± 5.0	0.012

BMI (mean ± SD)	26.7 ± 1.8	27.9 ± 3.4	29.9 ± 4.8	0.020
FFM (mean ± SD)	67.8 ± 6.0	69.3 ± 7.4	64.1 ± 7.8	0.006

Abbreviations: GDS, Geriatric Depression Scale; BMI, Body mass index; FFM, Free Fat Mass.

5. Discussion

There is consistent evidence that PA can positively impact the aging process, for instance in physical and neuropsychological dimensions (Daskalopoulou et al., 2017). However, it is unclear the quantification of the strength and nature of the relationship between PA and health outcomes. Consequently, accurate assessment of PA is crucial for quality research across the public health and exercise science fields, with repercussions in the clinic. Here, in a cohort of older adults, the main objective was to compare accelerometer-based estimates of PA (using a Xiaomi Mi Band 2®) with commonly used self-report questionnaires. Furthermore, the associations between PA and health outcomes were explored and PA profiles analyzed.

Overall, results show a poor to moderate correlation between self-reported and accelerometer-based estimates of PA and sedentary behavior. Briefly, and in line with previous findings (Boyle et al., 2015; Ferrari et al., 2020; M. C. N Nelson et al., 2019; Schmidt et al., 2020), low positive correlation coefficients were observed for IPAQ estimates (sedentary behavior, vigorous PA, and total PA) and moderate positive correlation for YPAS estimates of vigorous PA ($r = 0.42$, $p < 0.001$). The results also demonstrate a large variation between self-reported and Xiaomi Mi Band 2®-measured PA and sedentary time. As expected, the highest difference between objective and subjective methods was found for the sedentary time (7357.8 ± 940.9 $min.wk^{-1}$ for IPAQ and −885.0 ± 869.0 $min.wk^{-1}$ for YPAS), which follows a systematic review from Prince et al. (2020) indicating that self-report measures generally underestimate sedentary time when compared to device measures (Stephanie A. Prince et al., 2020). Surprisingly, we observed the lowest variation for vigorous PA. This result was unexpected since other authors have observed that the difference between the self-reported and objective measures increases with higher PA intensity levels (Dyrstad et al., 2014). Furthermore, a higher Xiaomi Mi Band 2® vigorous-intensity PA was noted when comparing with self-reported vigorous-intensity PA, whereas other studies have found higher values of self-reported vigorous-intensity PA (Dyrstad et al., 2014; Hagstromer et al., 2010; Stephanie A. Prince et al., 2020).

Since the correlation coefficient only evaluates the relationship between the variables and not the differences, it is not the best method for assessing comparability (Giavarina, 2015). Alternatively, the Bland–Altman plot quantifies the agreement between objective versus subjective methods. Overall, the results confirmed the lack of agreement between self-reported and accelerometer-based estimates of PA. Specifically, Xiaomi Mi Band 2®–measured PA minutes per day was plotted against the mean of the self-report and accelerometer for vigorous PA for IPAQ estimates. The mean difference was 9.1 ± 180.9 $min.wk^{-1}$ with the limits of agreement ranging from −345.4 to 363.6 $min.wk^{-1}$. Results indicate that the Xiaomi Mi Band 2® estimates of vigorous PA are consistently greater than IPAQ estimates. Additionally, the Bland–Altman plot for vigorous-intensity PA (IPAQ) provides evidence of proportional bias. These findings are consistent with previous studies and highlight the fact that measuring PA levels in the same person with these instruments leads to significant variations in magnitude and agreement (Boyle et al., 2015; M. C. Nelson et al., 2019; Schmidt et al., 2020).

Altogether, the present findings confirm that the general agreement between self-reported and accelerometer-measured PA is poor, and the correlation coefficients lower than what is recommended (Dyrstad et al., 2014). The lack of correlation and agreement between methods may be explained by the fact that the instruments do not measure the same constructs (Ferrari et al., 2020; Schmidt et al., 2020). While the accelerometer measures the motion through acceleration and uses laboratory-derived intensity thresholds to determine how much time was spent at different intensities of movement (sedentary, light, moderate, and vigorous), the questionnaires measure the time spent in specific domains and intensities (Ferrari et al., 2020; Schmidt et al., 2020). Furthermore, questionnaires use information based on self-report minutes of activity performed according to intensity, with a risk of misinterpretation of intensity associated with difficulties in remembering the frequency and duration of several activities especially in older adults (Ferrari et al., 2020). Regarding the study population, the assessment results indicated no limitations in cognitive function, physical function, and functionality, with all individuals being fully independent in daily living activities. The sample was categorized as overweight according to the BMI and the WHR ratio criteria, which are associated with metabolic risk factors. Other studies in the Portuguese population have shown that more than 20% of the adults are obese with an obesity prevalence higher in women (Oliveira et al., 2018). As expected, the body composition measures showed that women had significantly higher fat mass when compared to men and lower fat-free mass and muscle mass, with the values categorized within optimal values for both genders. In a recent study, Pereira et al. assessed body composition in a sample of Portuguese centenarians and observed mean values of FAT and FFM inferior to our study (Pereira da Silva et al., 2016). Indeed, aging is associated with changes in body composition mainly expressed in changes in body fat distribution and loss of muscle mass (Pereira da Silva et al., 2016; von Berens et al., 2020). Therefore, the assessment of body composition changes in the aging process could provide insights about the optimal weight for health status and physical performance (He et al., 2018; Pereira da Silva et al., 2016). The combination of low muscle mass and poor muscle function, i.e., sarcopenia, is a geriatric condition associated with adverse effects on function, quality of life, and survival (von Berens et al., 2020). Moreover, high body fat has been associated with poorer physical performance in older adults, and fat accumulation within the skeletal muscle is associated with muscle weakness and poor function (He et al., 2018). Remarkably, we observed that gender differences were found for most of the evaluated body composition parameters. A similar pattern was obtained in the aforementioned study in Portuguese centenarians (Pereira da Silva et al., 2016). Lastly, we observed a higher prevalence of obesity using anthropometric measures comparing to bioimpedance analysis, these results are in line with a previous study (Pereira da Silva et al., 2016).

Sedentary behavior has been described as an independent risk factor for poor health and mortality and is associated with obesity, muscle weakness, and mobility disability in older adults (Wullems et al., 2016). Concerning our study sample, the majority spent most of their daily activity in sedentary behavior. On average they spent 9088.9 $min.wk^{-1}$. (SD ± 735.7) in accelerometer-determined sedentary behavior, with no significant differences between genders. However, self-reported sedentary behavior (IPAQ estimates) was 247.4 ± 127.3 $min.d^{-1}$ with men reporting significantly higher levels. Therefore, study findings indicate that the participants assume that they are substantially less sedentary than they really are. A similar pattern was found in other studies (Ács et al., 2020; Stephanie A. Prince et al., 2020). The reported activities were predominantly walking, household, leisure, and gardening (Kyle et al., 2001). Also, a recent systematic review found that walking is the most frequently performed activity (Dyrstad et al., 2014). Moreover, results show a significant difference in PA between genders on domestic activities, sitting time, moderate activities, and total PA (IPAQ estimates), and in domestic activities and total PA (YPAS estimates), with higher values for women. Regarding levels of PA reported (IPAQ estimates) a significant difference for all intensities, except for vigorous-intensity, is noted. Therefore, the gender differences seem to influence these estimates only for self-reported PA. Concerning Xiaomi Mi Band 2®-measured PA, in general, participants spent more time in light compared to moderate or vigorous activities, as expected. No differences between gender in total minutes per day spent in all intensities for Xiaomi Mi Band 2®-measured PA were found. Approximately 45% of individuals have sedentary behavior and 48% are categorized as having met PA recommendations. According to the American College of Sports Medicine (ACSM), the older adult's recommendation is 150 min of PA with moderate-intensity or 75 min of vigorous-intensity, or an equivalent combination of moderate and vigorous PA per week to promote health (M. E. Nelson et al., 2007). Promoting PA in older adults is crucial to avoid the deterioration of physiological functions, body composition, physical function, and loss of mobility.

Concerning the association between health outcome variables, the results reveal a weak positive correlation between a Xiaomi Mi Band 2®–measured PA and GDS and gait speed. For IPAQ self-reported PA we found a moderate positive correlation with muscle mass and FFM, and a weak positive correlation with weight, WHR, GDS, and gait speed. Equally, YPAS self-reported PA shows a moderate positive correlation with muscle mass and FFM, and a weak positive correlation with weight. This finding was consistent with previous studies showing that self-reported and objectively measured PA associate differently with health outcomes. Future research is needed to better understand why different types of measures associate differently with health outcomes (Stephanie A. Prince et al., 2020). Regarding the cluster analysis, we observed that clusters C1 and C2, in which the participants meet the PA recommendations and with higher levels of PA, show better results in the evaluated health outcomes (GDS, speed, BMI, and FFM), as expected.

The strengths of this study are that the self-reported and the accelerometer data represent the same periods and provide new information about several physical functions, body composition variables, and PA levels in older adults, which is important for the knowledge of healthy aging strategies. Nonetheless, the small sample size and cross-sectional nature of the work limit (causality) inferences regarding the associations between PA and health outcomes. Moreover, the sample is not representative of the Portuguese older population, and a "healthy participant effect" must be considered; thus, findings cannot be widely generalizable. Concerning the limitations associated with accelerometry-based devices, it should be noted a low-sensitivity for sedentary behaviors, the limited ability for assessing low-intensity activities, and the lack of standard or generally acceptable placements for them (Mokhlespour Esfahani & Nussbaum, 2018). Cleland et al. (2013) evaluated the optimal placement of accelerometers and found that the hip was the best single location to record data. The lower accuracy for data from the wrist may be due, in part, to arm movements unassociated with the measured activity. Furthermore, they observed that by combining data from accelerometers on the wrist and hip the accuracy increased (Cleland et al., 2013). Boerema et al. also mentioned the influence of the placement, type of activity, and their interaction-effect. The authors recommended that to increase reliability and to reduce the variability, the optimal placement should be on the most lateral position of a participant's waist belt (Boerema, et al., 2014). Another limitation to consider is the cut-off point for accelerometer-measured sedentary behavior, which includes activities such as sitting and standing. Thus, this could increase the difference between the two methods since questionnaires only asks about time spent sitting and not standing and the accelerometer included standing time (Dyrstad et al., 2014). Finally, the choice of accelerometer cut points has a large influence on the comparison of the absolute results.

In summary, this study found large differences, a low correlation, and an absence of agreement, between self-reported and accelerometer-based estimates of PA, in a cohort of older adults, but the comparison between the two methods provides valuable information about habitual PA levels in senior populations.

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7. Author Contributions

Conceptualization, C.D., N.C.S., and J.M.P.; methodology, C.D.; formal analysis, C.D.; investigation, C.D.; data curation, C.D.; writing—original draft preparation, C.D.; writing—review and editing, C.D., N.C.S., and J.M.P.; supervision, N.C.S. and J.M.P.; funding acquisition, N.C.S. and J.M.P. All authors have read and agreed to the published version of the manuscript.

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9. Institutional Review Board statement

The study was approved by the local ethical committees (Approval Number 42-2018), conducted in accordance with the Declaration of Helsinki (59th Amendment), developed in compliance with the European General Data Protection Regulation, and approved by the Portuguese Data Protection Authority (Approval Number 11286/2017). The study goals and assessments were explained to participants during screening procedures.

10. Informed consent Statement

Informed consent was obtained from all subjects involved in the study.

11. Data Availability statement

Research data presented in this study are available on request from the corresponding author.

12. Conflicts of interest

The authors declare no conflict of interest.

13. References

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CHAPTER II

European Portuguese Version of the User Satisfaction Evaluation Questionnaire (USEQ): Transcultural Adaptation and Validation Study

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European Portuguese Version of the User Satisfaction Evaluation Questionnaire (USEQ): Transcultural Adaptation and Validation Study

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1. Abstract

Background: Wearable activity trackers have the potential to encourage users to adopt healthier lifestyles by tracking daily health information. However, usability is a critical factor in technology adoption. Older adults may be more resistant to accept novel technologies. Understanding the difficulties that older adults face when using activity trackers may be useful for implementing strategies to promote their use.

Objective: The purpose of this study was to conduct a transcultural adaptation of the User Satisfaction Evaluation Questionnaire (USEQ) into European Portuguese and validate the adapted questionnaire. Additionally, we aimed to provide information about older adults' satisfaction regarding the use of an activity tracker (Xiaomi Mi Band 2).

Methods: The USEQ was translated following internationally accepted guidelines. The psychometric evaluation of the final version of the translated USEQ was assessed based on structural validity using exploratory and confirmatory factor analyses. Construct validity was examined using divergent and discriminant validity analysis, and internal consistency was evaluated using Cronbach α and McDonald ω coefficients.

Results: A total of 110 older adults completed the questionnaire. Confirmatory factor analysis supported the conceptual unidimensionality of the USEQ (χ 24=7.313, P=.12, comparative fit index=0.973, Tucker–Lewis index=0.931, goodness of fit index=0.977, root mean square error or approximation=0.087, standardized root mean square residual=0.038). The internal consistency showed acceptable reliability (Cronbach α =0.677; McDonald ω =0.722). Overall, 90% of the participants reported excellent satisfaction with the Xiaomi Mi Band 2.

Conclusions: The findings support the use of this translated USEQ as a valid and reliable tool for measuring user satisfaction with wearable activity trackers in older adults, with psychometric properties consistent with the original version.

Keywords: elderly; reliability; satisfaction; seniors; technology; usability; validity; wearables

2. Introduction

The use of mobile health (mHealth) technology has greatly increased over the past decade. These technologies enable health promotion, self-monitoring of health-related behaviors (Steinert, Haesner et al. 2018, Turner-McGrievy, Jake-Schoffman et al. 2018, Schlomann, Seifert et al. 2019) and show potential in disease treatment and prevention in a cost-efficient and widely accessible manner (Melin, Bonn et al. 2020). Currently, mHealth covers a wide range of technologies, such as wearable devices and smartphone apps, for tracking different types of health-related data including physical activity (El-Amrawy and Nounou 2015, Melin, Bonn et al. 2020).

Activity trackers are sensor-based wearable devices that automatically track and monitor various indicators of physical activity (eg, steps, calories burned, and distance traveled), with some also able to record heart rate and sleep measures (Maher, Ryan et al. 2017, Rupp, Michaelis et al. 2018, Steinert, Haesner et al. 2018, Kononova, Li et al. 2019). The technology has the potential to help older adults with health self-management and self-efficacy by improving lifestyle behaviors and motivating compliance or attainment of daily activity goals (Maher, Ryan et al. 2017, Preusse, Mitzner et al. 2017, Schlomann, Seifert et al. 2019). Despite this potential, most older adults do not use activity trackers for their health-tracking needs. A possible explanation may be a matter of usability. Although it is a critical factor that can determine technology adoption, these devices have been mainly developed for a younger target group; thus, older adults may have difficulties due to usability barriers (Preusse, Mitzner et al. 2017, Steinert, Haesner et al. 2018).

Published by the International Organization for Standardization, ISO-9241-11 defines usability in terms of effectiveness, efficiency, and user satisfaction rating of a product in a specific environment, by a specific user, for a specific purpose (Bevan, Carter et al. 2016, Liang, Xian et al. 2018). Accordingly, user satisfaction can be thought of as a usability component, but it cannot be evaluated in the same manner as efficiency and effectiveness. Satisfaction is the user's attitude toward the system they use, affecting behavior intention for continuous or future use (Harrison, Flood et al. 2013, He, Kim et al. 2017, Chao 2019). Moreover, satisfaction depends on how comfortable the user feels using the system (Brooke 1996, Harrison, Flood et al. 2013, Bevan, Carter et al. 2016, Liang, Xian et al. 2018). Despite the importance of user satisfaction to ensure usability and the improved development of mHealth solutions, there is a gap in research assessing user satisfaction with mHealth (Melin, Bonn et al. 2020).

Currently, there are a few validated and widely used questionnaires to collect targeted user feedback for the evaluation of a system's usability. These include the System Usability Scale (SUS) (Brooke 1996), the Post-Study System Usability Questionnaire (PSSUQ) (Lewis 1995, Liang, Xian et al. 2018, Mohamad Marzuki, Yaacob et al. 2018, Zhou, Bao et al. 2019), and the Usefulness, Satisfaction and Ease of Use (USE) questionnaire (Gao, Kortum et al. 2018, Liang, Xian et al. 2018, Mohamad Marzuki, Yaacob et al. 2018). Of these, only the SUS (Martins, Rosa et al. 2015) and the USE (Dantas, Jegundo et al. 2017) questionnaires are available in European Portuguese for generalized evaluation of usability. Regarding user satisfaction questionnaires, a study by Melin et al (Melin, Bonn et al. 2020) presented the development of the mHealth Satisfaction Questionnaire, the Questionnaire for User Interaction Satisfaction (QUIS) (Chin, Diehl et al. 1988), and the User Satisfaction Evaluation Questionnaire (USEQ). Nonetheless, despite this, there is no validated questionnaire for measuring user satisfaction with technologies available in European Portuguese.

Therefore, this study aimed to provide a valid questionnaire to specifically evaluate user satisfaction with technologies in Portuguese older adults. For this, the USEQ was selected since it is a short but comprehensive questionnaire with a reasonable number of questions; importantly, it is clear and easy to understand (Gil-Gómez, Manzano-Hernández et al. 2017). We also aimed to evaluate user satisfaction with the Xiaomi Mi Band 2 among older adults. Regardless of spoken language, and despite a growing number of studies on subjective experiences of user satisfaction with and the usability and usefulness of wearable technologies, only a few studies have focused on older adults (Seifert, Schlomann et al. 2017, Kononova, Li et al. 2019, Schlomann, Seifert et al. 2019). Understanding whether a cohort of older adults is satisfied with these activity trackers is important to ensure devices can be successfully implemented in clinical and research settings (Farina and Lowry 2017).

3. Methods

The study was divided into two phases. Phase 1 addressed the translation of the USEQ questionnaire into European Portuguese and its cross-cultural adaptation. Phase 2 involved the assessment of the USEQ psychometric properties and its validation in the new context.

Translation and Cultural Adaptation of the USEQ

The USEQ is composed of 6 questions and uses a 5-point Likert scale for responses. The total score ranges from 6 (poor satisfaction) to 30 (excellent satisfaction). All questions are affirmative, except question 5, which is a negatively posed question. The numerical value of the affirmative questions is used to calculate the score. The negative question subtracts the numerical value of the response from 6 and then adds this result to the total score (Gil-Gómez, Manzano-Hernández et al. 2017). Since the

USEQ was designed to evaluate user satisfaction with virtual rehabilitation systems, the questionnaire comprises one item that specifically measures the perceived usefulness of using the technology for rehabilitation. Thus, in this study, we adapted this item to include an item that could be applied to general-purpose systems or across different types of mHealth.

The adapted English version of the USEQ was culturally and linguistically adapted to European Portuguese after obtaining formal authorization from the original author (Gil-Gómez (Gil-Gómez, Manzano-Hernández et al. 2017)). The process of translation followed the general guidelines provided by Lenz et al (Lenz, Gómez Soler et al. 2017) and the World Health Organization (World Health Organization, 2007). Briefly, it comprised the following steps: forward translation, translation review and reconciliation of content, back translation, preliminary version, pretesting, and final version (Multimedia Appendix 1). In step 1 (forward translation), the USEQ questionnaire was translated to European Portuguese by two independent English-proficient translators, whose native language is European Portuguese. In step 2 (translation review and reconciliation of content), the independent translations were reviewed by both forward translators as well as by an independent team member. A reconciliation version of the document was obtained. In step 3 (back translation), the reconciled version was translated from European Portuguese into English by independent translators fluent in both languages, who were blinded to the original USEQ version of the document. The retroversion was done as a quality control step and to verify that both versions were equivalent. In step 4 (preliminary version), all team members performed a comparative analysis between the back-translation and original version. The preliminary version was prepared after items were reviewed and a consensus was reached. Finally, in step 5 (pretesting), the preliminary version of the document was tested in a pilot study with a sample of 20 independent and representative individuals selected from those who will be administered the final questionnaire. The individuals were asked to provide feedback on their understanding of the questions, the preferred use of alternative words for a given expression, terms deemed unacceptable or offensive, and their opinion of the questionnaire. The information collected was used to improve and develop the final version of the USEQ.

Psychometric Properties and Validation of the USEQ

The psychometric validation of the final version of the USEQ was based on real data collection after the users' experience with the wearable activity tracker. The analyses included assessment of structural validity, construct validity, and internal consistency.

To provide evidence of construct validity, the participants' responses on the USEQ were correlated with the preexisting instruments that measure similar concepts—the SUS and the technology acceptance model 3 (TAM3; convergent validity). For divergent validity, the participants' responses on the USEQ were correlated with Mini-Mental State Examination (MMSE) scores (Campbell and Fiske 1959). Briefly, the SUS is the most widely used standardized questionnaire to measure perceived usability (Brooke 1996, Lewis 2018, Liang, Xian et al. 2018, Revythi and Tselios 2019), while the TAM is the most applied theoretical model for evaluating or predicting users' acceptance of new technologies (Davis 1989). Lastly, the MMSE is a widely accepted questionnaire to assess cognitive function in older adults (Myrberg, Hydén et al. 2020).

Participants and Data Collection

Following the application of inclusion and exclusion criteria, a total of 120 community-dwelling older adults (aged 64-75 years) from Northern Portugal were recruited to the study. The primary exclusion criteria were an inability to understand informed consent and neuropsychiatric and neurodegenerative disorders. Among the recruited participants, a final sample of 110 participants completed the usability test of the wearable activity tracker.

A baseline characterization was performed through a sociodemographic questionnaire and a standardized clinical interview. Moreover, since individual differences, including demographics, cognitive state, and emotional state influence individuals' perceptions regarding the technology (Montag and Panksepp 2017), we included a neuropsychological evaluation to obtain mood (Geriatric Depression Scale [GDS]) (Yesavage, Brink et al. 1982) and global cognitive profiles (MMSE) (Guerreiro, Silva et al. 1994).

For usability testing, the Xiaomi Mi Band 2 was selected among several commercially available wearable activity trackers, since it is ergonomic, accessible, easy to operate, and offers the best price-quality ratio. The device provides general health monitoring, combining sensors that allow objective assessment of activity levels, heart rate, and sleep patterns (El-Amrawy and Nounou 2015, Puri, Kim et al. 2017, Mičková, Machová et al. 2019). The participants used a Xiaomi Mi Band 2 over 15 days while performing their normal daily activities. They were instructed to wear the activity tracker continuously. After concluding the usage testing period, participants were asked to provide information about their experience. This was attained through application of the USEQ (Gil-Gómez, Manzano-Hernández et al. 2017) to evaluate user satisfaction, the TAM 3 (Venkatesh and Bala 2008) to collect information about technology acceptance, and the SUS for perceived usability (Martins, Rosa et al. 2015).

Statistical Analysis

Data analysis was performed using IBM SPSS Statistics (version 26; IBM Corp), and JASP (version 0.11.1). Descriptive statistics (mean, median, standard deviation [SD], minimum, maximum, skewness, and kurtosis) were calculated for each variable. Normality was considered adequate if absolute values for skewness and kurtosis were above 2.0 and 7.0, respectively (Curran, West et al. 1996, Kim 2013).

Structural Validity

The creators of the original scale analyzed the factor structure through principal component analysis (PCA) (Gil-Gómez, Manzano-Hernández et al. 2017). Results indicated two components with an eigenvalue greater than 1. The first component had all six items and explained 43% of the variance, and the second component had only four items (items 1, 4, 5, and 6), only two of which had factor loadings greater than 0.5. Therefore, after the analysis of the scree plot, they considered a one-factor solution explaining 42.9% of the variance to be appropriate.

Before conducting exploratory factor analysis (EFA) with our data, the "parameters" R package was used to decide the number of factors to extract. The solution for one dimension was supported by 6 (42.9%) methods of 14 (acceleration factor, standard error [SE] scree, Tucker–Lewis index [TLI], root mean square error of approximation [RMSEA], Adjusted root mean square residual [CRMS], Bayesian Information Criterion [BIC]) (Makowski 2018). As PCA is a data reduction technique that does not conduct to a latent variable model, principal axis factoring was used to extract the latent factor. Variables with factor loadings above 0.4 were extracted. Before the analysis, the appropriateness of the data for factor analysis was examined using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett test of sphericity (Dziuban & Shirkey 1974, Howard 2016). Regarding the sample size for the EFA, there is no consensus on the number of participants required to perform the analysis (Osborne, Costello et al. 2004, Kyriazos 2018). Hatcher et al (Hatcher 1994) recommend a minimum subject to item ratio of at least 5:1, with a minimum of 100 subjects. The number of components was determined by Kaiser criteria (retaining factors with eigenvalues greater than 1), scree plot inspection (Howard 2016), and parallel analysis [(Patil Vivek H).

Subsequently, confirmatory factor analysis (CFA) was performed using maximum likelihood estimation. The factor loadings were used as local indices of goodness of fit as well as the following goodness-of-fit indices and thresholds for a good fit: chi-square test ($\chi 2$; $P>.05$), chi-square value divided by degrees of freedom (a ratio of ≤3), comparative fit index (CFI≥0.90), Tucker–Lewis Index (TLI≥0.90), goodness of fit index (GFI ≥0.90), root mean square error of approximation (RMSEA<0.08) and standardized root mean square residual (SRMR≤0.08) (Hu and Bentler 1999, Schermelleh-Engel, Moosbrugger et al. 2003, Hooper, Coughlan et al. 2008).

Ideally, a CFA should be performed in a subsequent study using another sample (validation sample) (Fabrigar, Wegener et al. 1999). However, due to having an insufficient sample size to perform the analysis in two subsamples, the same sample was used for both approaches (EFA and CFA).

Internal Consistency

Internal consistency was assessed using both Cronbach α and McDonald ω coefficients (Şimşek and Noyan 2013, Trizano-Hermosilla and Alvarado 2016). Cronbach α is the most widely used measure of reliability. However, it overestimates the true composite reliability and is negatively biased when used to measure the reliability of ordinal variables (Costello and Osborne 2005, Şimşek and Noyan 2013). Given the ordinal response format of USEQ items, McDonald ω was used to overcome these limitations, providing a more accurate approximation of the scale reliability (Gadermann, Guhn et al. 2012). Cronbach α and McDonald ω coefficients over 0.70 are considered indicators of satisfactory item homogeneity (Cronbach 1951, Gadermann, Guhn et al. 2012). Item-total and inter-item correlations were analyzed, considering cutoff values over 0.30 and under 0.70, respectively (Ferketich 1991).

Construct Validity: Convergent and Divergent Validity

Convergent and divergent validity were estimated using Spearman correlation (r). It was hypothesized a priori that the USEQ score would be positively correlated with the SUS score and TAM 3 score, while correlation was not expected with the MMSE score. A coefficient of r=0.3 is assumed to provide evidence of convergent and divergent validity (Cohen 1992, Schober et al. 2018).

USEQ Scores

Descriptive statistics and normality were assessed for the USEQ's total score. Correlations between USEQ scores and demographic as well as mood and global cognitive characteristics were estimated using Spearman correlation.

Ethics Statement

The study was conducted in accordance with the Declaration of Helsinki and was approved by the local and national ethics committees (approval number 42-2018). The study goals and assessments were explained to potential participants. All participants provided written informed consent before study enrollment.

4. Results

Study Participants

A total of 110 participants completed the USEQ questionnaire. Demographic, mood, and global cognitive characteristics of the sample are presented in Table 1. Participants had an average age of 68.41 (SD 3.11) years with a mean of 7.95 (SD 5.38) years of education.

Table 1. Characteristics of the study participants (N=110).

Characteristics	Values
Age, years, mean (SD)	68.41 (3.11)
Gender, male, n (%)	50 (45.5)
Education, years of formal schooling, mean (SD)	7.95 (5.38)
Education, years of formal schooling, mean (SD)	26.95 (2.00)
Geriatric Depression Scale, total score, mean (SD)	6.05 (4.58)

Study participants responded to all items of the USEQ. Descriptive statistics for USEQ items are presented in Table 2. Given the ordinal nature of the variables assessed, item distribution demonstrates some degree of nonnormality. In fact, the majority of data collected in behavioral research does not follow univariate normal distributions (Curran, West et al. 1996, Norman 2010). For the USEQ total score, the results reveal acceptable values for both skewness (sk=−2.02) and kurtosis (k=3.96), showing no severe violation of normality. Regarding the individual items, the kurtosis value was not acceptable for item 1; thus, it was excluded from further analysis.

Table 2. Descriptive statistics for User Satisfaction Evaluation Questionnaire items.

Items	Minimum	Maximum	Median	Mean (SD)	Skewness	Kurtosis
Item 1	1	5	5	4.80 (0.59)	-3.81	17.67
Item 2	3	5	5	4.82 (0.47)	-2.66	6.46
Item 3	2	5	5	4.65 (0.71)	-2.21	4.50
Item 4	2	5	5	4.47 (0.75)	-1.30	0.98
Item 5	1	5	5	4.65 (0.93)	-2.71	6.15
Item 6	1	5	5	4.70 (0.69)	2.68	8.30

Structural validity

An exploratory factor analysis was conducted on the 5 items of the USEQ. The Kaiser-Meyer-Olkin measure demonstrated adequacy for the analysis (KMO=0.629) as a value above 0.6 indicates an adequate sample size (Howard 2016). The Bartlett sphericity test (χ 210=126, $P<.001$) indicated that the correlation between the items is sufficient to perform the analysis. The analysis showed that the one-factor solution explains 47% of the variance (Table 3) and comprises all items with factor loadings higher than 0.3. Our findings corroborated the decision of the original questionnaire authors, who considered a one-factor solution to be appropriate.

Table 3. Factor matrix containing obliquely unrotated factor loadings of principal axis factoring (forcing one-factor solution). The eigenvalue and the percentage of variance explained by the factor are also shown.

Items	**Factor 1**
Item 2	0.568
Item 3	0.870
Item 4	0.680
Item 5	0.403
Item 6	0.346
Eigenvalues	2.345
% of Variance	46.9

A one-factor solution CFA model was tested for the interference dimension, as hypothesized by the original authors (Gil-Gómez, Manzano-Hernández et al. 2017). All 5 items were loaded onto a single latent variable. Table 4 shows goodness-of-fit measures for the model, revealing acceptable measures for the following indices: χ^2_4=7.313, P=.12; CFI=0.973, TLI=0.931, GFI=0.977, RMSEA=0.087, and SRMR=0.038 (Schneider 2012). The final model is presented in Figure 1.

Table 4. Fit indices for confirmatory factor analysis model.

Indices	Model
Chi-square value (df)	7.313 (4)
Chi-square value to df ratio	1.83
P value	0.120
CFI	0.973
Tucker–Lewis Index	0.931
Goodness of fit index	0.977
Root mean squared error of approximation	0.087
Standardized root mean squared residual	0.038

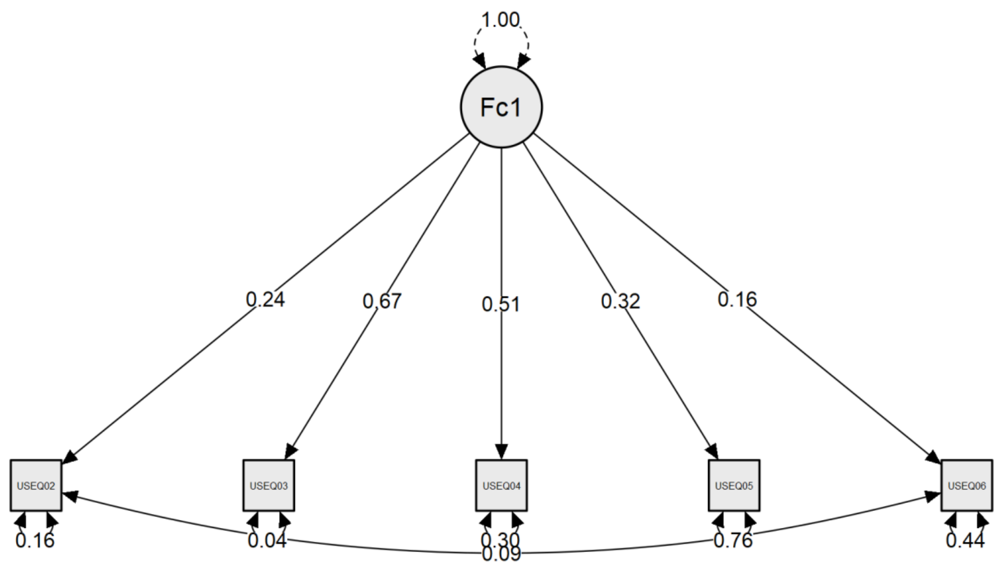

Figure 1. Path diagram and standardized estimates for the one-factor model of the User Satisfaction Evaluation Questionnaire.

Internal consistency

Analysis of the internal consistency showed acceptable reliability (Cronbach α=0.677; McDonald ω =0.722), indicating a reliability homogeneity of the items for the one-factor solution. The corrected item-total correlation values ranged from 0.080 to0.654, showing an adequate correlation of each item and suggesting adequate scale homogeneity. The inter-item correlations were all below 0.70, indicating nonredundancy of items (Table 5).

Table 5. Inter-Item Correlation Matrix.

	Item 2	Item 3	Item 4	Item 5
Item 3	0.495	—[a]	—	—
Item 4	0.270	0.654	—	—
Item 5	0.251	0.317	0.327	—
Item 6	0.397	0.219	0.207	0.080

[a]Not applicable.

Convergent and divergent validity

The association between the USEQ and SUS was moderate in magnitude (r=0.43, P<.001), and strong between TAM 3 factor "perceived ease of use" (r=0.690, P<.001) and TAM 3 factor "perceptions of external control" (r=0.571, P<.001). No significant correlation was observed between USEQ and MMSE (r=0.042, P=.661).

USEQ scores

To rate the USEQ score, the following classification was used: poor (0-5), fair (5-10), good (10-15), very good (15-20), or excellent (20-25) [62].

The mean USEQ score was 23.30 (SD 2.40), indicating an excellent level of satisfaction with the activity tracker (Xiaomi Mi Band 2; Table 6).

Table 6. Scores obtained on the User Satisfaction Evaluation Questionnaire for the original scale with 6 items and the newly proposed scale with 5 items.

Items	Minimum	Maximum	M (SD)	Skewness	Kurtosis
USEQ (5 Items)	14	25	23.30 (2.40)	-1.81	2.99
USEQ (original)	17	30	28.07 (2.84)	-2.01	3.96

All participants reported user satisfaction experiences above "good," with 90% of all participants reporting excellent satisfaction with the device. Furthermore, a significant correlation (r=–0.319, P=.001) between depressive mood and user satisfaction was noted; a higher score on the GDS (i.e., higher depressive mood) was negatively associated with satisfaction with the device (Table 7).

Table 7. Spearman bivariate correlations between User Satisfaction Evaluation Questionnaire scores and demographic, mood, and global cognitive characteristics.

	Gender	Age	Years of education	Mini-Mental State Examination	Geriatric Depression Scale
r_s	–0.005	–0.120	0.124	0.042	–0.319[a]
p	.96	.21	.20	.66	.001

[a]Significant correlation.

5. Discussion

Physical activity is associated with health benefits, a decreased burden of disease, and a decrease in all-cause mortality in adults (Steinert, Haesner et al. 2018). Nowadays, wearable activity trackers provide the opportunity to increase physical activity levels through continuous monitoring (Kononova, Li et al. 2019), which may be especially beneficial for older adults. However, over 75% of the over-65 age group state that they require assistance to use new technologies (Steinert, Haesner et al. 2018). Usability studies on wearable activity trackers are needed to better understand the barriers that older adults face when using these technologies. In a cohort of older adults, this study aimed to provide a valid questionnaire to evaluate user satisfaction using an activity tracker (Xiaomi Mi Band 2).

The results from the translation phase show that the items were easy to understand and that there were no semantic problems. Moreover, the translated items were considered equivalent to the original version. In particular, the USEQ was found to be a simple and easy-to-understand questionnaire with an appropriate number of questions to apply in older populations. Validity evidence was obtained with 5 questions, maintaining the original one-factor structure. Similar to the original study by Gil-Gómez et al [23], reporting that the one-factor solution explained about 43% of the variance, here an approximate 47% of the variance was explained by the one-factor solution.

Confirmatory factor analysis showed acceptable fit indexes (χ 24=7.313, P=.12, CFI=0.973, TLI=0.931, GFI=0.977, RMSEA=0.087, and SRMR=0.038). However, it is recommended to evaluate structural validity in another independent study. The reliability results show that the European Portuguese version of the USEQ yielded an adequate internal consistency (Cronbach α=0.677; McDonald ω=0.722) in a sample of older individuals. Overall, results indicate that the psychometric properties of the European Portuguese version of the USEQ are comparable with those of the original version, and therefore may be used for the evaluation of satisfaction concerning other technologies, including wearable activity trackers.

Convergent validity is one of the fundamental aspects of construct validity and it refers to how closely the new questionnaire is related to other variables and other measures of the same construct. Regarding convergent validity, as expected, the USEQ correlated with the SUS (r=0.43, P<.001). The SUS is a widely used standardized questionnaire for the assessment of the perceived usability of technology. Thus, a moderate positive correlation was expected, given that the two questionnaires are meant to measure similar constructs. TAM 3 has been one of the most influential models regarding technology acceptance. It distinguishes two concepts influencing an individual's intention to use new technology: perceived ease of use and perceived usefulness. Therefore, we also expected a correlation between some constructs of the TAM 3 and the USEQ. Indeed, results showed a positive moderate correlation of the USEQ with the TAM 3 factors "perceived ease of use" ($r=0.690$, $P<.001$) and "perceptions of external control" ($r=0.571$, $P<.001$).

No demographic variables were found to be significantly correlated to user satisfaction with the device. However, a higher depressive mood, as evaluated by the GDS, was negatively associated with the satisfaction perceived by participants using the device. Similarly, a recent study investigating the impact of depressive symptoms on measures of web user experience found a significant association between depressive symptoms and subjective user experience (Thielsch and Thielsch 2018). These results indicate that mood may be a factor influencing technology usability and may warrant further guidance and/or targeted approaches in the use of these technologies by specific populations.

Regarding user satisfaction with the Xiaomi Mi Band 2, the device achieved a score of 23.30 (SD 2.40) in the USEQ, demonstrating an excellent reported level of satisfaction and thus suggesting suitability for older adults. Furthermore, results showed that item 4—"Is the information provided by the system clear?"—which is related to the perceived ease of use, yielded the lowest score. This result may suggest that older adults could have difficulties in understanding the information provided by the activity tracker, which should be noted by manufacturers. The perceived ease of use refers to the degree to which a person perceives how easy it is to use the technology and is one of the primary factors that affect an individual's intention to use new technology (Davis 1989, Preusse, Mitzner et al. 2017, Rupp, Michaelis et al. 2018). This kind of difficulty is especially interesting considering the age of the participants enrolled in the study. Older adults tend to perceive technologies as difficult to use due to usability problems related to poor memory, decreased vision, and poor literacy (Li and Luximon 2018), but this may not necessarily be the case for all older individuals. Thus, results should be interpreted with caution and future studies should include cohorts with different characteristics (for instance, higher school levels or those that have been [early] adopters of different types of technologies).

Concerning limitations, the study was conducted using a convenience sample; therefore, the participants may not represent the entire older population. Moreover, if the sample used in this study is more homogenous than the wider population on the common factors, this can lead to attenuation in correlations and can influence the strength or bias of correlations among variables Fabrigar, Wegener et al. 1999). Future studies should have a larger sample, and it would be beneficial to the study to maximize variance on measured variables relevant to the constructs of interest Fabrigar, Wegener et al. 1999). It would also be of value to evaluate the long-term use of this device and motivations for long-term use. Moreover, studies combining quantitative and qualitative methods, such as interviews, would also be valuable to explore older adults' perceptions and experiences, and to provide details about user behaviors, user needs, and specific problems that quantitative measures cannot address. Finally, further user satisfaction studies of older adults using activity trackers should include other devices. This would ensure that such devices can be effectively implemented in clinical and research settings to promote physical activity.

In conclusion, the European Portuguese version of the USEQ has adequate psychometric properties consistent with the original version, supporting its use as a valid and reliable tool for measuring user satisfaction in older adults. Furthermore, we adapted USEQ to a generic questionnaire for user satisfaction that can be used with several mHealth technologies, including smartphones, patient monitoring devices, tablets, mobile health apps, personal digital assistants, and other wireless devices. Finally, this study has contributed to the currently available and growing body of information on the usability of wearable technologies among older adults.

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7. Authors' Contributions

CD contributed to conceptualization, data curation, formal analysis, investigation, methodology, and writing (original draft, review, and editing). PSC contributed to formal analysis, methodology, and writing (review and editing). NCS contributed to funding acquisition, supervision, and writing (review and editing). JMP contributed to funding acquisition, supervision, and writing (review and editing). All authors reviewed and approved the final version of the manuscript.

8. Conflicts of Interest

None declared.

9. Abbreviations

BIC: Bayesian Information Criterion

CFA: confirmatory factor analysis

CFI: comparative fit index

CRMS: Adjusted root mean square residual

EFA: exploratory factor analysis

GDS: Geriatric Depression Scale

GFI: goodness of fit index

KMO: Kaiser-Meyer-Olkin

mHealth: mobile health

MMSE: Mini-Mental State Examination

PCA: principal component analysis

PSSUQ: Post-Study System Usability Questionnaire Usefulness

QUIS: Questionnaire for User Interaction Satisfaction

RMSEA: root mean square error of approximation

SE: standard error

SRMR: standardized root mean square residual

SUS: System Usability Scale

TAM 3: technology acceptance model

TLI: Tucker–Lewis index

USE: Satisfaction and Ease of Use questionnaire

USEQ: User Satisfaction Evaluation Questionnaire

WHO: World Health Organization

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11. Supplementary material

Supplementary Table 1. The translation process of the User Satisfaction Evaluation Questionnaire.

English version	Forward translation	Back translation
Did you enjoy your experience with the system?	Foi agradável usar esta tecnologia?	Was it enjoyable to use this technology?
Were you successful using the system?	Conseguiu usar com sucesso esta tecnologia?	Were you able to successfully use this technology?
Were you able to control the system?	Foi capaz de controlar esta tecnologia?	Were you able to control this technology?
Is the information provided by the system clear?	A informação fornecida por esta tecnologia foi clara?	Was the information provided by this technology clear?
Did you feel discomfort during your experience with the system?	Sentiu-se desconfortável durante o uso desta tecnologia?	Did you feel uncomfortable while using this technology?
Do you think that this system will be helpful for your rehabilitation?	Considera que esta tecnologia será útil na sua reabilitação?	Do you think this technology will be useful in your rehabilitation?

Supplementary Table 2. Preliminary version tested in a pilot study with 20 participants and final European Portuguese version obtained after the pilot study.

Preliminary version	Final version
Foi agradável usar esta tecnologia?	Gostou de usar esta tecnologia?
Conseguiu usar com sucesso esta tecnologia?	Foi bem-sucedido a usar esta tecnologia?
Foi capaz de controlar esta tecnologia?	Foi capaz de controlar esta tecnologia?
A informação fornecida por esta tecnologia foi clara?	A informação fornecida por esta tecnologia foi clara?
Sentiu-se desconfortável durante o uso desta tecnologia?	Sentiu-se desconfortável durante o uso desta tecnologia?
Considera que esta tecnologia será útil na sua reabilitação?	Considera que esta tecnologia será útil na melhoria da sua saúde?

Supplementary Table 3. Original item vs. corresponding item in English and European Portuguese versions.

Espanhol – Versão Original	English version	European Portuguese final version
Te has divertido com el sistema?	Did you enjoy your experience with the system?	Gostou de usar esta tecnologia?
Superaste com êxito lo planteado por el sistema?	Were you successful using the system?	Foi bem-sucedido a usar esta tecnologia?
Has sentido que tenias el control de la situación com el sistema?	Were you able to control the system?	Foi capaz de controlar esta tecnologia?
Te ha parecido clara la información que te ha dado el sistema?	Is the information provided by the system clear?	A informação fornecida por esta tecnologia foi clara?
Te has sentido incomodo em algun momento durante el ejercicio?	Did you feel discomfort during your experience with the system?	Sentiu-se desconfortável durante o uso desta tecnologia?
Crees que este tratamento resultará útil para tu rehabilitacion?	Do you think that this system will be helpful for your rehabilitation?	Considera que esta tecnologia será útil na melhoria da sua saúde?

CHAPTER III

Usability, acceptability, and satisfaction of a wearable activity tracker in adults: an observational study in a real-life context.

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Usability, acceptability, and satisfaction of a wearable activity tracker in adults: an observational study in a real-life context.

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1. Abstract

Background: The use of activity trackers has significantly increased over the last few years. This technology has the potential to improve the levels of physical activity and health-related behaviors in older adults. However, despite the potential benefits, the rate of adoption is low among older adults. Therefore, understanding how technology is perceived may potentially offer insight to promote its use.

Objective: This study aimed to (a) assess acceptability, usability, and user satisfaction with Xiaomi Mi Band 2® in Portuguese community-dwelling older adults in a real-world context; (b) explore the mediating effect of the usability on the relationship between user characteristics and satisfaction, and (c) examine the moderating effect of user characteristics on the relationship between usability and user satisfaction.

Methods: Older adults used the Xiaomi Mi Band 2® over 15 days. The user experience was evaluated through the Technology Acceptance Model (TAM 3), System Usability Scale (SUS), and User Satisfaction Evaluation Questionnaire (USEQ). An integrated framework for usability and user satisfaction was used to explore user experience. Statistical data analysis included descriptive data analysis, reliability analysis, confirmatory factor analysis, and mediation and moderation analysis.

Results: A sample of 110 older adults with an average of 68.41 years old (SD = 3.11) completed the user experience questionnaires. User acceptance was very high [PEOU= 6.45 (SD ± 0.78), PEC = 6.74 (SD ± 0.55), CANX= 6.85 (SD ± 0.47), 6.60 (SD ± 0.97)]. The usability was excellent with an average score of 92.70 (SD ± 10.73), and user satisfaction was classified as a good experience 23.30 (SD ± 2.40). The mediation analysis confirmed the direct positive effect of usability on satisfaction (β = 0.530; p < 0.01) and direct negative effect of depression on usability (β = -0.369; p < 0.01). Lastly, the indirect effect of usability on user satisfaction was higher in individuals with lower GDS levels.

Conclusion: Findings demonstrate that the Xiaomi Mi Band 2® is suitable for older adults. Furthermore, the results confirmed usability as a determinant of older satisfaction with the technology and extended the existing knowledge in wearable activity trackers in older adults.

Keywords: aging; fitness trackers; health monitoring; seniors; Technology Acceptance Model; user experience.

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2. Introduction

Wearable devices are electronic devices that allow users to automatically track and monitor their physical fitness metrics, including the number of steps, level of activity, walking distance, calories burned, heart rate, and sleep patterns (Shih, Han et al. 2015, Rupp, Michaelis et al. 2018, Steinert, Haesner et al. 2018, Shin, Jarrahi et al. 2019). Over the last few years, these devices have also become increasingly popular among researchers interested in assessing and intervening on physical activity (PA)-related behaviors in real-world contexts. Wearable devices offer the opportunity to collect objective PA data in a less intrusive and inexpensive manner and provide tailored and personalized interventions in real-time (Rupp, Michaelis et al. 2018, Turner-McGrievy, Jake-Schoffman et al. 2018, Alley, van Uffelen et al. 2019). In fact, overall, academic and industry research has shown that their use can increase PA levels and promote a healthier lifestyle through real-time self-monitoring of health-related behaviors (Maher, Ryan et al. 2017, Seifert, Schlomann et al. 2017, Liang, Xian et al. 2018, Rupp, Michaelis et al. 2018, Turner-McGrievy, Jake-Schoffman et al. 2018, Kononova, Li et al. 2019). However, despite these potential benefits, older adults still show slow technology adoption rates (Berkowsky, Sharit et al. 2018, Kononova, Li et al. 2019), possibly because these technologies are mainly developed for a younger target group, without considering health psychology or gerontology theories (Seifert, Schlomann et al. 2017). Consequently, older adult users may have usability barriers to technology adoption (Preusse, Mitzner et al. 2017, Steinert, Haesner et al. 2018). Furthermore, factors associated with normal aging, such as physical and cognitive decline, could limit the ability to use the technology (Berkowsky, Sharit et al. 2018).

A better understanding of older adults' intentions to use activity trackers, and examining actual usage behavior, is becoming increasingly relevant; however, only a few studies have been conducted to determine older adults' perceptions (Mercer, Giangregorio et al. 2016, Seifert, Schlomann et al. 2017, Kononova, Li et al. 2019, Schlomann, Seifert et al. 2019). Therefore, the present study aimed to understand the user experience and acceptability of an activity tracker (Xiaomi Mi Band 2®), throughout daily life activities, in a cohort of community-dwelling older adults.

Theoretical framework

After carrying out a literature search, three major key concepts were identified regarding user experience and technology adoption: technology acceptance, usability, and user satisfaction. Variables were also selected regarding user characteristics, such as cognitive function, mood, and education, which may significantly influence user experience to develop our model. Thus, the theoretical framework was designed to explore older adults' user experience with the Xiaomi Mi Band 2®, by combining different theories as next described, while also enabling the examination of the impact of usability and individual characteristics on user satisfaction with technology.

Technology acceptance model

Technology acceptance is an important factor in determining the long-term adoption of activity trackers (Rupp, Michaelis et al. 2018). The Technology Acceptance Model (TAM) is the most applied theoretical model for evaluating or predicting users' acceptance of new technologies. TAM was adapted from the Theory of Reasoned Action (TRA) (LaCaille 2013) and was initially developed by Davis (1989) (Davis 1989). This model assumes that the perceived ease of use (PEOU) and perceived usefulness (PU) are the primary factors influencing an individual's intention to use new technology (Davis 1989, Preusse, Mitzner et al. 2017, Rupp, Michaelis et al. 2018). PEOU refers to the degree to which a person perceives how easy it is to use the technology, and PU refers to how using the technology will improve performance (Davis 1989). Moreover, PEOU and PU can be influenced by various external factors, including both the device and user characteristics (Davis 1989, Rupp, Michaelis et al. 2018, Revythi and Tselios 2019). The usability seems to be predictive of acceptance regarding the device characteristics because they directly relate to the PEOU and PU and may moderate attitudes and behavioral intentions (BI) to use a system (Rupp, Michaelis et al. 2018).

The original TAM model was extended to TAM 2 by Venkatesh and Davis (2000) to explain PU and usage intentions in terms of social influence and cognitive instrumental determinants (Venkatesh and Davis 2000). Later, Venkatesh and Bala (2008) updated the model, including other variables affecting PEOU, such as individual differences (computer self-efficacy, computer anxiety, and computer playfulness), perception of external control, and system characteristics-related adjustments (perceived enjoyment, and objective usability) (Venkatesh and Bala 2008).

System Usability Scale

Initially proposed by John Brooke in 1986, the System Usability Scale (SUS) is the most widely used standardized questionnaire to measure perceived usability (Brooke 1996, Lewis 2018, Liang, Xian et al. 2018, Revythi and Tselios 2019). Recent literature shows that several studies extend the TAM by incorporating the SUS (Scholtz, Mahmud et al. 2016, Pande, Saravu et al. 2017, Revythi and Tselios 2019). Although the SUS has been assumed to be unidimensional, recent research reveals that the SUS has two sub-scales – usability and learnability–, with items 4 and 10 providing the learnability dimension and the other 8 items the usability dimension (Lewis and Sauro 2009, Martins, Rosa et al. 2015).

According to ISO-9241-11, usability refers to the effectiveness, efficiency, and user satisfaction rating of a product in a specific environment by a particular user for a particular purpose. More precisely, effectiveness refers to which of the system's intended goals can be achieved; efficiency is the effort required for a user to achieve the goals; and satisfaction depends on how comfortable the user feels using the system (Brooke 1996, Bevan, Carter et al. 2016, Liang, Xian et al. 2018). Therefore, usability is a critical factor that directly affects the use and adoption of technology by older adults.

User Satisfaction Evaluation Questionnaire

The literature on technology acceptance has included many model variants and extensions, including user satisfaction as a key indicator of user acceptance (Mather, Caputi et al. 2002, Dalcher and Shine 2003, Wixom and Todd 2005, Ghobakhloo, Zulkifli et al. 2010, He, Kim et al. 2017, Chao 2019, Ho, Ho et al. 2019). Moreover, satisfaction has been described as a predictor of behavior intention (Chao 2019). The User Satisfaction Evaluation Questionnaire (USEQ) was initially designed by Gil-Gómez et al. (2017) to evaluate the satisfaction of the users with virtual rehabilitation systems (Gil-Gómez, Manzano-Hernández et al. 2017). Recently, the USEQ was adapted and validated into European Portuguese by Domingos et al. to evaluate an activity tracker (Xiaomi Mi Band 2®) in older adults, showing psychometric properties consistent with the original version (Domingos C 2020).

User characteristics

In a theoretical framework developed by Venkatesh (2008), individual differences, such as personality and demographics (e.g., traits or individuals' states, gender, and age), were suggested to influence individuals' perceptions of PU and PEOU (Venkatesh and Bala 2008). Specifically, personality is related to individual differences in cognitive, emotional, and motivational aspects of mental states that result in stable behavioral action (Montag and Panksepp 2017). Moreover, personality has been found to affect technology perceptions and acceptance (Svendsen, Johnsen et al. 2013, Rupp, Michaelis et al. 2018).

Additionally, older individuals may show age-related declines, including attention, memory, and processing speed, which may further impact how they interact with the technology (Rupp, Michaelis et al. 2018). The aging process is also associated with a decline in visual faculties, i.e., visuospatial functioning, visual acuity, color discrimination, and contrast sensitivity, crucial for learning new information and executing technology-based tasks (Li and Luximon 2018). Thus, researchers have focused on the impact of cognitive abilities, self-efficacy, and technology-related anxiety in technology acceptance (Berkowsky, Sharit et al. 2018). Lastly, compared to younger adults, the senior population may be more resistant to adopt new technologies due to cultural factors, education, and experience (Rupp, Michaelis et al. 2018).

Research framework and hypotheses

This study uses a model based on SUS to measure usability and USEQ to measure user satisfaction and incorporate individual characteristics, such as education, mood, and cognitive performance (Figure 1).

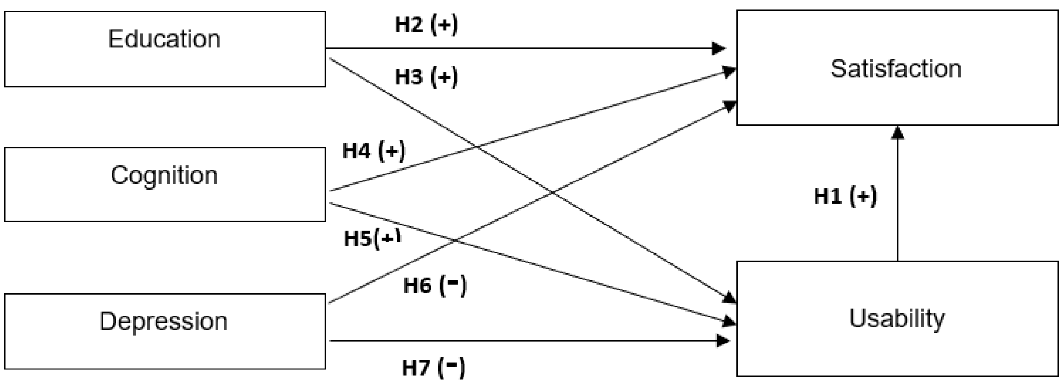

Figure 1. Research hypothesis framework.

The design was founded on the basic theory studied to provide a clear causal relationship between independent variables (exogenous) on the dependent variables (endogenous). The model has five variables exploring the user experience with Xiaomi Mi Band 2® in older adults.

The following hypotheses were formulated:

H1: Usability has a positive effect on satisfaction.

H2: Education has a positive effect on satisfaction.

H3: Education has a positive effect on usability.

H4: Cognition has a positive effect on satisfaction.

H5: Cognition has a positive effect on usability.

H6: Depression has a negative effect on satisfaction.

H7: Depression has a negative effect on usability.

Additionally, user characteristics' potential moderating effect on the direct effect between usability and satisfaction was tested separately for each variable (Figure 2).

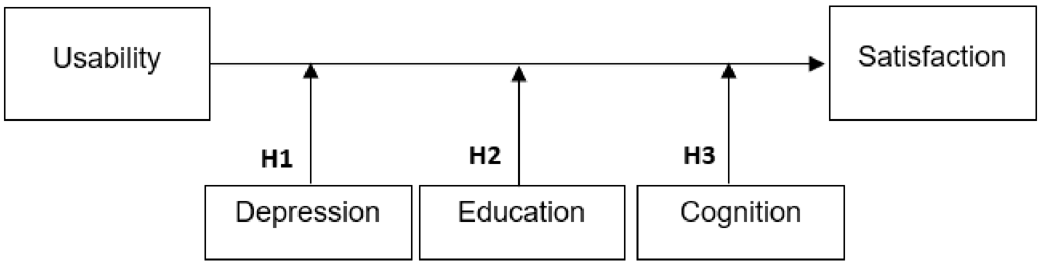

Figure 2. Moderating effect of user characteristics.

3. Methods

Participants and research ethics

A priori sample size calculation and power analysis were performed using GPower. Considering that the study is part of a larger project, which used a wearable device to measure and quantify free-living PA in older adults, a total of 120 participants was determined assuming an effect size of 0.32 (Lautenschlager, Cox et al. 2012, Hogan, Mata et al. 2013, Gajewski and Falkenstein 2016), an alpha of 0.05, 0.95 of power and 23% of dropout rate. The power analysis for this user experience study was conducted considering the sample size calculated previously and a medium effect size (Scholtz, Mahmud et al. 2016) confirmed a power of 0.92. Moreover, the rule of thumb to determine sample size in multiple regression analyses confirmed that the minimum sampling requirements for the analysis were met (Green 1991). Therefore, a total of 120 participants, representative of the general older Portuguese population living in the community within the age group 65-74 years, were recruited from health centers and local gyms in Northern Portugal. The older adults were defined according to World Health Organization, which considers older people, in developed world economies, as those aged 65 or older. To reduce variability due to the age effect, we used the first 10-year age group in the same way as Eurostat publication — Ageing Europe (Eurostat 2020).

The applied exclusion criteria comprised inability to understand informed consent, diagnosed neuropsychiatric and neurodegenerative disorders, or disability that limited independent walking, limited visual, auditory, and/or fine motor skills. Participants with previous experience with other wearable activity trackers were not excluded from the study. A final sample of 110 participants was enrolled in the study. The study ran from April 2018 to July 2019.

The study was conducted according to the Helsinki declaration and approved by the local and ethics committees (Approval Number 42-2018), developed in compliance with the new General Data Protection Regulation, and approved by the Portuguese Data Protection Authority (Approval Number 11286/2017). Study goals and assessments were explained during screening procedures. All participants provided written informed consent before study enrollment, which included consent to their data processing.

Data collection and instruments

A baseline characterization was performed through a sociodemographic questionnaire, and a neuropsychological evaluation to obtain mood (Geriatric Depression Scale – GDS) (Yesavage, Brink et al. 1982) and global cognitive profiles (Mini-Mental State Examination – MMSE) (Guerreiro, SILVA et al. 1994). For screening "cognitive impairment" via the MMSE the following cut-off values were used: individuals with no education, <15 points; 1 to 11 years of school completed, <22 points; and >11 years of school completed, <27 points (7). For assessment of the presence of depressive symptomatology via the GDS, the cut-off value considered was a total number of depressive symptoms superior to 11 (9).

To assess the users' experience, the Xiaomi Mi Band 2® was provided to participants to continuously wear over 15 days, while performing their normal daily activities. The wearable was returned after the testing period for data analysis. In other studies, testing periods range from 3 days to 7 days (Vooijs, Alpay et al. 2014, Mercer, Giangregorio et al. 2016, Farina and Lowry 2017, Puri, Kim et al. 2017); since a 7-day testing period is a short-term user experience, we decided to extend this period to 15 days. Upon completing the usage period, participants were also asked to provide information about their user experience. The TAM 3 (Venkatesh and Bala 2008) was used to collect information about technology acceptance, the SUS (Martins, Rosa et al. 2015) for perceived usability, and the USEQ (Gil-Gómez, Manzano-Hernández et al. 2017, Domingos C 2020) for user satisfaction.

Xiaomi Mi Band 2®

The selection of wearable activity tracker was based on a review of several different commercially available devices on the market (El-Amrawy and Nounou 2015, Liang, Xian et al. 2018, Xie, Wen et al. 2018). The selection criteria included their popularity in the health tracking device market, availability, continuous monitoring of PA without a smartphone, price, battery life, various sensors data captured, and ability to export data. The Xiaomi Mi Band 2® was selected since, at the study time, offered the best price-quality ratio, had an estimated battery life of almost 30 days, was ergonomic, accessible, easy to operate, and did not require continuous communication with a smartphone. The system combines sensors that allow the objective assessment of daily free-living PA, with its algorithms calculating steps, intensity, energy expenditure, and distance traveled (El-Amrawy and Nounou 2015, Puri, Kim et al. 2017, Mičková, Machová et al. 2019).

Technology acceptance model

The TAM 3 was adapted to the context of the use of activity tracking technologies by older adults, and the key dimensions of acceptance were investigated using the following constructs: PEOU, PEC (perception of external control), computer anxiety (CANX), behavioral intention (BI), and USE. PEOU was measured using all four items adapted from TAM3; PEC using two; CANX using three, BI and USE were measured using the only item on the original scale. The supplementary Table 1 presents a list of items for all the constructs. TAM items were measured on a 7-point Likert-scale, starting from "strongly disagree" to "strongly agree." The mean scores of each item were computed and the mean of means of each construct was calculated and used to perform statistical analysis (Venkatesh and Bala 2008).

System usability scale

The SUS is a 10-item questionnaire, consisting of five positive and five negative statements, with the five responses for each statement ranging from “strongly agree” to “strongly disagree” (Supplementary

Table 2). The SUS score is calculated by taking 1 from all the scores on odd-numbered items and subtracting 5 from the even-numbered items scores. The sum of the scores is then multiplied by 2.5 to give an overall SUS score and range from 0 (extremely poor usability) to 100 (excellent usability) (Martins, Rosa et al. 2015). The value of 68 is considered the average for the SUS score; a score above or less than 68 is considered above average or below average, respectively (Bangor, Kortum et al. 2009, Brooke 2013). The grade rankings of scores proposed by Bangor were here used to provide a more meaningful basis for the SUS Score interpretation (Bangor, Kortum et al. 2009).

User Satisfaction Evaluation Questionnaire

The USEQ is a 6-item questionnaire with a five-point Likert Scale (supplementary Table 3). The total score ranges from 6 (poor satisfaction) to 30 (excellent satisfaction). All items are affirmative, except item 5, which is a negative item. The numerical value of the affirmative items is used to calculate the score. The negative item subtracts the numerical value of the response from 6 and then adds this result to the total score. The USEQ score is evaluated using the following classification: poor (0-5), fair (5-10), good (10-15), very good (15-20), or excellent (20-25) satisfaction (Gil-Gómez, Manzano-Hernández et al. 2017, Domingos C 2020).

Statistical analysis

The statistical analysis was organized to address the following aims: (i) explore the mediating effect of the usability on the relationship between user characteristics and satisfaction; and (ii) examine the moderating effect of user characteristics on the relationship between usability and user satisfaction. Briefly, the statistical analysis was performed according to the following steps: (i) descriptive statistics; (ii) Instruments psychometric proprieties; (iii) structural equation modeling (SEM); and (iv) moderation analysis.

Descriptive statistics

Descriptive data analysis was performed using IBM SPSS Statistics (version 26) to depict the characteristics of the study. Descriptive statistics, including frequency, percentage, mean, standard deviation, minimum, maximum, skewness, and kurtosis, were calculated for each variable. Normality was considered adequate if absolute values for skewness and kurtosis were above 3.0 and 10.0, respectively (Kline 2015, Diop, Zhao et al. 2019). The percentage of missing values across the variables was analyzed. Methods for handling missing data were not applied since there were no missing data.

Instrument's validation

Before structural modeling, the measurement model of latent variables for their dimensionality/structure and reliability was assessed.

Confirmatory factor analysis (CFA) was conducted using JASP (Version 0.11.1) to examine the structure of SUS (used to measure usability) and USEQ (used to measure user satisfaction). Variables with factor loadings above 0.4 were included. To assess the goodness of fit of the model, the following indices and thresholds were applied: chi-square ($\chi 2$, p>0.05), $\chi 2$ /degrees of freedom ratio (≤3); Comparative Fit Index (CFI≥0.90); Tucker–Lewis Index (TLI≥0.90); Goodness of Fit Index (GFI ≥0.90); Root Mean Squared Error of Approximation (RMSEA<0.08) and Standardized Root Mean Squared Residual (SRMR≤0.08) (Hu and Bentler 1999, Schermelleh-Engel, Moosbrugger et al. 2003, Hooper, Coughlan et al. 2008).

Reliability analysis was performed using IBM SPSS Statistics (version 26) to analyze the internal consistency of item-responses of SUS and USEQ instruments. Reliability was estimated using McDonald's omega (ωt) coefficient (Şimşek and Noyan 2013, Trizano-Hermosilla and Alvarado 2016). Given ordinal response format items, the McDonald's (ωt) provides more accurate estimates of reliability than Cronbach's α (Costello and Osborne 2005, Gadermann, Guhn et al. 2012, Şimşek and Noyan 2013). Coefficients values over 0.70 are considered indicators of satisfactory item homogeneity (Cronbach 1951, Gadermann, Guhn et al. 2012).

Structural equation modeling (SEM)

SEM was applied to check the hypothesis relationship between the proposed factors that directly and indirectly influence older adult's user satisfaction (structural model) with technology. SEM allows to analyze the structural relationship between measured variables and latent variables. The derived scores for usability and user satisfaction were supported by CFA.

Data were analyzed using IBM SPSS AMOS (version 25) and the parameters were estimated by the maximum likelihood method. The significance level of 5% was used as a threshold for the research proposition testing. To determine whether the model was reasonable and acceptable the following indices were considered: $\chi 2$, $\chi 2$/degrees of freedom ratio CFI, TLI, GFI, and RMSEA. The criteria for an acceptable model fit were the same as those reported for the CFA.

To assess multicollinearity, the inspection of the correlation matrix of the predictor variables (education, MMSE, GDS, and usability), and the analysis of the variance inflation factor (VIF) and tolerance, was performed (IBM SPSS Statistics (version 26)). The tolerance values close to 1 were considered as an indicator of low multicollinearity, whereas a value close to zero potential indicator of collinearity problem (Senaviratna, Cooray et al. 2019, Shrestha 2020). Moreover, the VIF =1 was considered an indicator that the independent variables are not correlated, and 1< VIF < 5 an indicator that the variables are moderately correlated to each other (Shrestha 2020).

Moderation analysis

Moderation analysis was performed to examine whether the relationship between usability (predictor) and user satisfaction (outcome variable) depended on user characteristics (moderator). The analysis was performed using the MedMod package in Jamovi (version 1.2.27) software. The significance of the interaction term of usability on user satisfaction at specific values (-1 SD, mean, +1 SD) of GDS, education, and MMSE (moderators), was assessed, exploring when the effect of usability in user satisfaction depends on the level of the moderating test variable.

4. Results

Study Participants

A total of 110 participants completed the final assessment after the testing period. Table 1 summarizes the demographic, mood, and global cognitive characteristics of the sample. Participants have a mean age of 68.41 (SD±3.11) years old, and 46% were identified as males. The mean years of formal education were 7.95 (SD± 5.38).

Table 1. Characteristics of the study participants (N=110).

Characteristics	n	Percentage (%)	M ± SD
Gender, n (%) males	50	46	
Age, years			68.41 ± 3.11
[64, 70[	73	66	
≥ 70	37	34	
Education, years			7.95 ± 5.38
[1, 4]	58	53	
[5, 11]	24	22	
≥12	28	26	
MMSE, total score			26.95 ± 2.00
[22, 27[	41	63	
≥ 27	69	37	
GDS, total score			6.05 ± 4.58
> 11	17	16	

Abbreviations: MMSE, Mini Mental State Examination; GDS, Geriatric Depression Scale; BMI, Body mass index; WC, waist circumference; HP, hip circumference; WHR, waist-to-hip ratio; FAT, Fat Mass; FFM, Free Fat Mass; Muscle, Muscle mass; Mineral, Mineral body density; BCM, Body Cell Mass; ADL, Activities of Daily Living; IADL, Instrumental Activities of Daily Living.

Instruments descriptive statistics

The results of descriptive statistics for the instruments (TAM 3, SUS, and USEQ) are presented in Table 2, Table 3, and Table 4, respectively. The skewness and kurtosis values indicate some degree of non-normality. In reality, most behavioral research data does not follow univariate normal distributions (Curran, West et al. 1996, Norman 2010). Moreover, the results reveal a severe violation of normality for the following items and constructs: USEQ1, SUS1, SUS3, SUS5, SUS9, PEOU3, and perceptions of external control (PEC) and computer anxiety (CANX). Thus, these were excluded for further path analysis.

Table 2. Descriptive statistics for TAM 3 items.

Items	Minimum	Maximum	M	SD	Skewness	Kurtosis
Perceived Ease of Use						
PEOU 1	2	7	6.28	1.08	-1.62	2.25
PEOU 2	1	7	6.06	2.01	-1.97	2.22
PEOU 3	3	7	6.84	0.60	-4.37	20.92
PEOU 4	3	7	6.60	0.92	-2.42	5.11
PEOU score	3.50	7.00	6.45	0.78	-1.48	1.54
PEOU final	3.67	7.00	6.31	0.94	-1.25	0.24
Perceptions of External control						

PEC1	3	7	6.55	0.97	-2.38	5.19
PEC2	4	7	6.94	0.41	-6.84	46.91
PEC score	4.00	7.00	6.74	0.55	-2.62	7.34
Computer Anxiety						
CANX1	6	7	6.99	0.10	-10.49	110.00
CANX2	1	7	6.86	0.83	-6.72	45.64
CANX3	2	7	6.71	0.97	-3.49	11.44
CANX score	4.33	7.00	6.85	0.47	-3.55	12.72
Behavioral intention						
BI	1	7	6.60	0.97	-3.00	10.84
USE (hours)	13	24	23.85	1.12	-8.99	85.16

Abbreviations: M, mean; SD, standard deviation.

Analyses comparing the concordance of absolute values between the IPAQ and Xiaomi Mi Band 2® showed the older adults reported less sedentary time and less moderate-intensity time compared with the accelerometer data (Table 3).

Table 3. Descriptive statistics for SUS items.

Items	**Minimum**	**Maximum**	**M**	**SD**	**Skewness**	**Kurtosis**
Item 1	1	5	4.71	0.65	-2.82	9.87
Item 2	1	5	1.44	1.03	2.40	4.70
Item 3	2	5	4.92	0.36	-5.81	40.38

Item 4	1	5	1.38	1.04	2.51	4.75
Item 5	1	5	4.85	0.56	-4.47	23.01
Item 6	1	5	1.28	0.83	3.12	9.26
Item 7	1	5	3.58	0.78	-2.15	4.88
Item 8	1	5	1.30	0.92	3.06	8.16
Item 9	3	5	4.86	0.46	-3.42	10.71
Item 10	1	5	1.41	1.08	2.52	4.95
SUS Score	55	100	92.70	10.73	-1.61	1.77

Abbreviations: M, mean; SD, standard deviation.

Table 4. Descriptive statistics for USEQ items.

Items	Minimum	Maximum	M	SD	Skewness	Kurtosis
Item 2	3	5	4.82	0.47	-2.66	6.46
Item 3	2	5	4.65	0.71	-2.21	4.50
Item 4	2	5	4.47	0.75	-1.30	0.98
Item 5	1	5	4.65	0.93	-2.71	6.15
Item 6	1	5	1.28	0.83	3.12	9.26
USEQ Score	14	25	23.30	2.40	-1.81	2.99

Abbreviations: M, mean; SD, standard deviation.

Instruments psychometric proprieties

As reported by Domingos et al. (2020) the CFA supported the conceptual unidimensionality of the USEQ [($\chi2$ (4) = 1.83, p = 0.120, $\chi2$/df =1.83; CFI = 0.973, TLI = 0.931, GFI = 0.977, RMSEA= 0.087, SRMR = 0.038)] (Domingos C 2020). Furthermore, the CFA analysis for the SUS showed satisfactory values for the following indexes: CFI = 0.816; GFI= 0.928; SRMR = 0.074. The fit Indices for the model are presented in Table 5.

Table 5. Confirmatory factor analysis for instruments.

Fit Indices	USEQ	SUS
χ2	7.313	30.074
Df	4	9
χ2/Df	1.83	3.34
p	0.120	< .001
CFI	0.973	0.816
TLI	0.931	0.694
GFI	0.977	0.928
RMSEA	0.087	0.146
SRMR	0.038	0.074

Abbreviations: $\chi2$, chi-square; df, degrees of freedom; CFI, Comparative Fit Index; TIL, Tucker–Lewis Index; GFI, Goodness of fit index; RMSEA, Root Mean Squared Error of Approximation; SRMR, Standardized Root Mean Squared Residual.

Regarding internal consistency, for the SUS questionnaire's reliability was calculated only with items included in path analysis (SUS2, SUS4, SUS6, SUS7, SUS8, SUS10). Moreover, the USEQ showed acceptable reliability (Cronbach's α = 0.677; McDonald's ω = 0.722), as reported by Domingos et al.

(2020) (Domingos C 2020). The McDonald's ω coefficients showed acceptable values for SUS and USEQ questionnaires ranging from 0.712 to 0.722, respectively.

Users' experience

The high ratings of TAM 3 indicate excellent technology acceptance by the participants. Overall, the average ratings for user experience with Xiaomi Mi Band 2® were 6.45 (SD ± 0.78) for PEOU, 6.74 (SD ± 0.55) for PEC, 6.85 (SD ± 0.47) for CANX, and 6.60 (SD ± 0.97) for BI. Furthermore, the participants reported an average of 23.85 (SD ± 1.12) hours of use per day (Table 2). These results indicate that participants found that Xiaomi Mi Band 2® is an easy-to-use and easy-to-control device, potentially perceiving its usefulness regarding health benefits and having the intention to use it in the future.

Regarding usability, the overall SUS score ranged from 55 to 100 (92.70 ± 10.73), with 96% of the participants reporting a score above the acceptability baseline of the SUS. Moreover, 46% of the participants classified the activity tracker achieved as best Imaginable (Table 6). Thus, these results suggest that the Xiaomi Mi Band 2® is a usable wearable activity tracker among older adults.

Finally, all participants reported a user satisfaction experience above the USEQ baseline value defined as a good experience, with a mean USEQ score of 23.30 (SD ± 2.40) (Table 4). Moreover, 86% of the participants rated the satisfaction with the Xiaomi Mi Band 2® as excellent (Table 6). Still, despite older adults reporting good satisfaction with the device, concerns were noted regarding the clarity of the technology's information.

Table 6. User experience classification for usability and satisfaction.

Classification	n (%)
Usability (SUS)	
Ok	8 (7.3)
Good	16 (14.5)
Excellent	36 (32.7)
Best imaginable	50 (45.5)
Satisfaction (USEQ)	
Good	2 (1.8)
Very good	14 (12.7)
Excellent	94 (85.5)

Abbreviations: n, frequency; %, percentage.

The structural equation modeling for user satisfaction

Table 7 shows fit indexes for the structural model, showing acceptable values for the $\chi 2/df= 1.67$ and RMSEA= 0.079 indexes and values slightly less than the threshold for a good model fit for the following indexes: GFI= 0.880 TLI = 0.818, CFI= 0.868. Based on these indexes, the model has a moderate acceptable fit.

Table 7. Fit indices for the hypothesized model

Model Fit Index	
χ^2	110.475
Df	66
χ^2***/Df***	1.67
p	< .000
GFI	0.880
TLI	0.818
CFI	0.868
RMSEA	0.079

Abbreviations: χ2, chi-square; df, degrees of freedom; CFI, Comparative Fit Index; TIL, Tucker–Lewis Index; GFI, Goodness of fit index; RMSEA, Root Mean Squared Error of Approximation; SRMR, Standardized Root Mean Squared Residual.

The path diagram of the model is presented in Figure 3. Coefficients within paths are standardized regression coefficients from regressions.

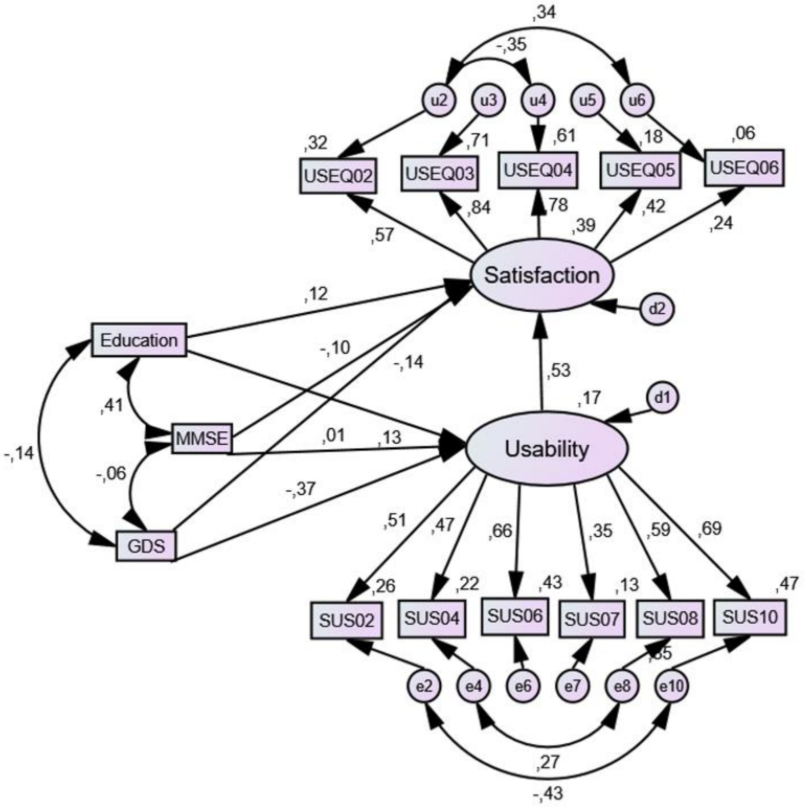

Figure 3. Path diagram for the research model.

Table 8 summarizes the results of hypothesis testing, including standardized coefficients and significance levels. Specifically, results show that usability was significantly and positively associated with user satisfaction (β = 0.530; $p < 0.01$), thereby supporting hypotheses 1. On the other hand, depression was significantly and negatively associated with usability (β = -0.369; $p < 0.01$), supporting hypotheses 7.

Individual characteristics (education, cognition, and depression) collectively explained 16.8% of usability variance. Furthermore, individual characteristics and usability collectively explained 39.1% of the variance in satisfaction. Specifically, depression negatively impacted usability and satisfaction, with a significant effect on usability; while, regarding education, a positive, but not significant, usability and satisfaction effect was observed. Despite confirming the theoretical model, most research hypotheses were not statistically proven with adequate goodness of fit. Nonetheless, usability seems to be a strong predictor of user satisfaction.

Considering the possible multicollinearity issues in the SEM model, the absolute values of correlation coefficients were calculated and ranged from 0.009 to 0.45. The tolerance values ranged from 0.82 to 0.87 and the VIF values from 1.15 to 1.22, indicating that no independent variable is in a perfect linear function with other any independent variable.

Table 8. Results of hypothesis testing based on standardized path coefficients for the research model.

Hypothesis	**Estimate**	**S.E.**	**C.R.**	**P**
H1: Usability > Satisfaction	0.530	0.089	3.008	0.003
H2: Education > Satisfaction	0.121	0.005	1.194	0.232
H3: Education > Usability	0.130	0.011	1.147	0.251
H4: Cognition > Satisfaction	-0.098	0.013	-0.999	0.318
H5: Cognition > Usability	0.011	0.029	0.104	0.917
H6: Depression > Satisfaction	-0.140	0.006	-1.376	0.169
H7: Depression > Usability	-0.369	0.014	-3.010	0.003

Abbreviations: S.E., standard error; C.R., critical ratio.

Moderation analysis

Moderating effect of GDS

Usability significantly predicted satisfaction (β = 0.43; p <.001) (Table 9). The interaction effect of usability × GDS was not significant (β = -0.028; p < 0.058), however since the p-value is approximately 0.05, we can conclude there is a tendency to infer that the effect of the satisfaction is dependent on GDS levels. The simple slopes of the interaction at -1 SD, mean, and +1 SD of GDS are plotted in Figure 4.

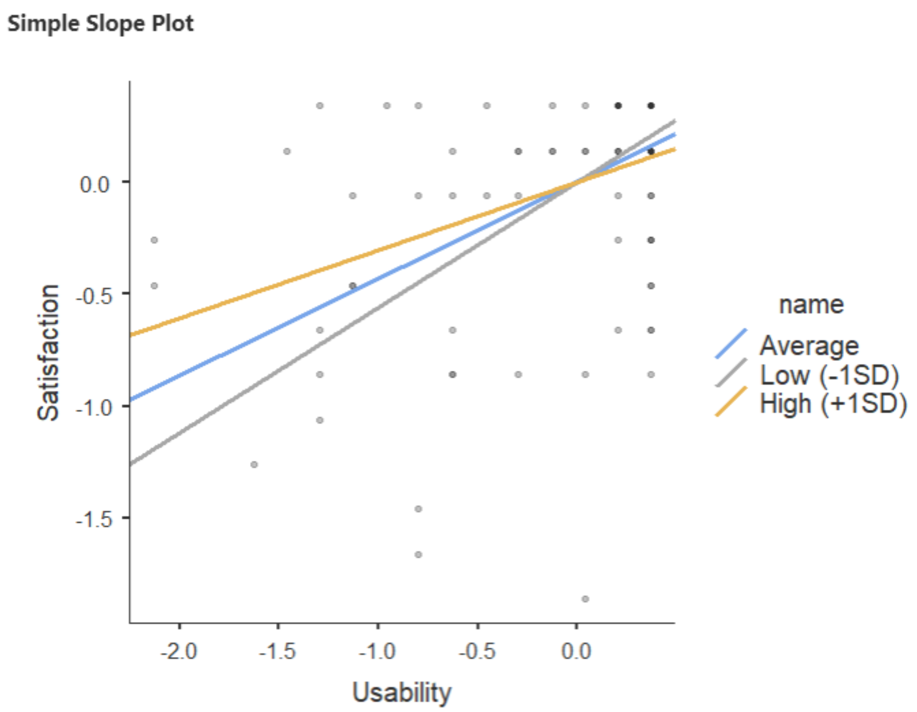

Figure 4. Simple slope plot for moderating effect of GDS and usability in the prediction of user satisfaction.

Results indicate that a significant association for high and low values of low GDS, respectively, in the same direction (β = 0.30, p <.001; β = 0.56, p <.001) (Table 10). Moreover, the effect of usability on user satisfaction through GDS was higher in individuals with lower GDS levels.

Table 9. Estimates for the moderating effect of GDS and usability in the prediction of user satisfaction.

	Estimate	S.E.	Z	P
Usability	0.43	0.082	5.28	< .001
GDS	-0.012	0.009	-1.34	0.18
H1: Usability × GDS	-0.028	0.015	-1.90	0.058

Table 10. Effect of the usability on satisfaction at different levels of GDS.

	Estimate	**S.E.**	**Z**	**P**
Average	0.43	0.083	5.22	< .001
Low (-1SD)	0.56	0.135	4.16	< .001
High (+1SD)	0.30	0.070	4.36	< .001

Moderating effect of education

Usability significantly predicted satisfaction (β = 0.36; p <.001) (Table 11). However, the interaction effect of usability × education in the direct path between usability and user satisfaction was not significant (β = 3.63e-4; p < 0.98). Results from simple slope estimates for the effect of usability on satisfaction indicated that education did not moderate the relationship between these variables (Table 12). Moreover, the interaction plot (Figure 5) showed no difference in simple slopes at -1 SD, mean, and +1 SD.

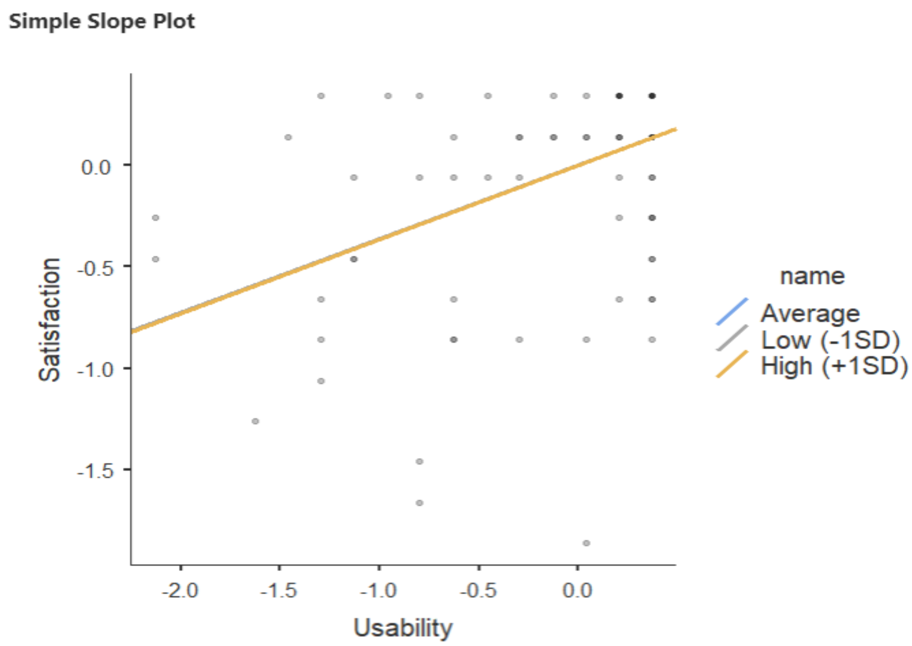

Figure 5. Simple slope plot for moderating effect of education and usability in the prediction of user satisfaction.

Table 11. Estimates for the moderating effect of education and usability in the prediction of user satisfaction.

	Estimate	S.E.	Z	P
Usability	0.36	0.070	5.23	< .001
Education	0.004	0.008	0.522	0.60
H2: Usability × Education	3.63e-4	0.017	0.022	0.98

Table 12. Effect of the usability on satisfaction at different levels of education.

	Estimate	S.E.	Z	P
Average	0.364	0.067	5.23	< .001
Low (-1SD)	0.362	0.098	3.71	< .001
High (+1SD)	0.366	0.128	2.85	0.004

Moderating effect of MMSE

The interaction effect of usability × MMSE in the direct path between usability and user satisfaction was not significant (β = 0.014; $p < 0.657$) (Table 13). The simple slopes of the interaction at -1 SD, mean, and +1 SD of GDS are plotted in Figure 6. Results indicate positive relationship between usability and satisfaction for both low (β = 0.352; $p < .001$) and high (β = 0.407; $p < .001$) MMSE levels (Table 14). Additionally, the results suggested that the indirect effect of usability on user satisfaction through MMSE is higher for individuals with higher levels of MMSE.

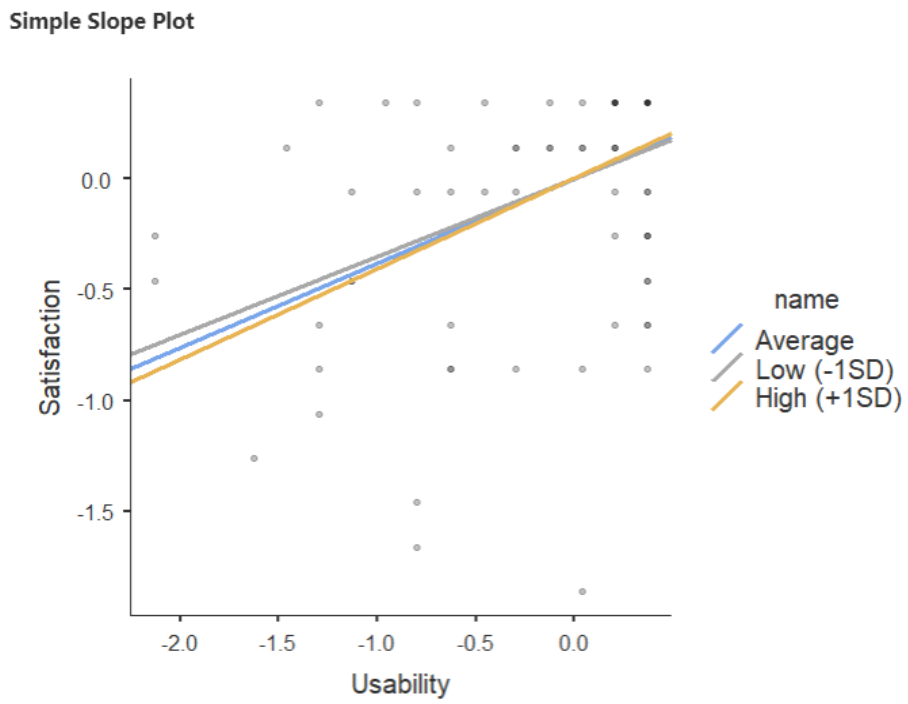

Figure 6. Simple slope plot for moderating effect of MMSE and usability in the prediction of user satisfaction.

Table 13. Estimates for the moderating effect of MMSE and usability in the prediction of user satisfaction.

	Estimate	**S.E.**	**Z**	**P**
Usability	0.380	0.070	5.46	< .001
MMSE	-0.008	0.020	-0.387	0.699
H3: Usability × MMSE	0.014	0.031	0.445	0.657

Table 14. Effect of the usability on satisfaction at different levels of MMSE.

	Estimate	**S.E.**	**Z**	**P**
Average	0.380	0.070	5.45	< .001
Low (-1SD)	0.352	0.079	4.44	< .001
High (+1SD)	0.407	0.105	3.87	< .001

Discussion

In recent years, wearable activity trackers are part of a rapidly growing trend in biomedical research and medicine (Mercer, Giangregorio et al. 2016, Bassett, Freedson et al. 2019, Keogh, Dorn et al. 2020). These devices have been employed in behavior change interventions due to the potential to motivate individuals to comply with a daily activity goal (Mercer, Giangregorio et al. 2016, Bassett, Freedson et al. 2019). Since most older adults have insufficient levels of PA, these technologies may be especially beneficial in middle-aged and older age groups. Nonetheless, it is reported that only 16% of activity tracker owners are 55 to 64 years of age and 7% over 65 (Steinert, Haesner et al. 2018), indicating that possibly these devices may not be feasible or acceptable to older adults (Lyons, Swartz et al. 2017). Therefore, it is necessary to understand how older adults perceive these new technologies. Thus, to better understand potential barriers to using these technologies, the acceptability, usability, and user satisfaction experience with Xiaomi Mi Band 2® were examined in a population of older adults.

Results from users' experience indicate an excellent technology acceptance with high ratings of TAM 3 in all constructs, including PEOU, PEC, CANX, and BI. Previously, Puri et al. (2017) found a moderate level of acceptance (65%) for Xiaomi Mi Band 2® among the Canadian community-dwelling older adults; where, interestingly, participants reported a significantly higher acceptance rate for the Xiaomi Mi Band 2® when compared to Microsoft Band (Puri, Kim et al. 2017). In the present study, no other devices were tested, thus, not allow for any comparison between wearable devices.

Concerning usability, all participants scored their experience above the acceptability baseline for SUS. Thus, results indicate that Xiaomi Mi Band 2® has excellent usability for older adults in this specific context. Participants also reported a user satisfaction experience above the USEQ baseline value defined as a good experience, suggesting excellent user satisfaction. Nonetheless, such a large score on

SUS (92.70 ± 10.73) was surprising. In a study by Liang et al. (2018), and albeit the Xiaomi Mi Band 2® being one of the devices that achieved the highest score among several selected wearable devices with distinct market performance, its SUS score was 65.12 ± 14.73 (Liang, Xian et al. 2018). Possible explanations range from the intrinsic motivation to use the device and how the device is supplied; therefore, such aspects should be evaluated in future studies.

This study also examined factors influencing user satisfaction with Xiaomi Mi Band 2®, based on the proposed theoretical framework. The hypothetical model was supported by moderate acceptable fit indices values (χ 2/Df= 1.67, GFI= 0.880 TLI = 0.818, CFI= 0.868, and RMSEA= 0.079). Furthermore, two of the testing hypotheses were proven. Overall, results indicate that usability is a significant predictor of user satisfaction (β = 0.530; $p < 0.01$), which, in turn, was negatively affected by depression symptoms (β = -0.369; $p < 0.01$). The model shows that individual characteristics explain 16.8% of the usability variance and 39.1% of the variance in satisfaction collectively with usability. Specifically, a significant negative effect of depression on usability was found.

Additionally, user characteristics' potential moderating effect on the interaction between usability and user satisfaction were also examined. Results suggested that GDS moderates the usability effect on user satisfaction, and the effect is higher in individuals with lower GDS levels. However, we did not observe significant moderating effects for education and MMSE on the interaction between usability and user satisfaction, contrary to our expectations. Future research should explore additional moderating effects through the user characteristics, including personal traits, motivational and cultural aspects to enable a better understanding of the factors that may influence user satisfaction and consequently facilitate technology adoption.

Overall, our results align with a recent study investigating the impact of depressive symptoms on web user experience measures, indicating that mood may be a factor influencing technology usability (Thielsch and Thielsch 2018). Additionally, recent research investigating the relationship between user perceptions and user characteristics has shown that older adults demonstrate positive attitudes toward mobile technologies and report technologies' complexity. User characteristics, such as age, processing speed, and attention, significantly influence older adults' usage behavior. Furthermore, the education level was found to be positively correlated to the diversity of use. Probably, individuals with higher education levels are typically more motivated to accept new concepts. The authors also mentioned that the usability problems could be attributed to poor memory, decreased vision, and poor literacy, thus older adults tended to perceive the technologies as difficult to use (Li and Luximon 2018).

Beyond the proposed research framework of the study, we aimed to use an integrated technology acceptance model and user satisfaction, similar to other studies (Mather, Caputi et al. 2002, He, Kim et al. 2017, Chao 2019). However, due to the severe violation of normality observed in TAM 3 constructs, we cannot integrate the technology acceptance model in path analysis. Nonetheless, previous research has shown a significant influence of PEOU on user satisfaction, with the latter proposed to be a key predictor of BI (Ghobakhloo, Zulkifli et al. 2010, He, Kim et al. 2017, Ho, Ho et al. 2019). Additionally, Chao (2019) showed that perceived enjoyment, effort expectancy, and performance expectancy have a significantly positive effect on satisfaction (Chao 2019); thus, it would have been relevant to the inclusion of these variables to predict satisfaction.

Regarding usability, Venkatesh (1996) theorizes that PEOU is affected by the objective usability of a specific system only after a direct experience with the system; where, perceptions about the PEOU are determined solely by usability features, which in turn form the basis for acceptance or rejection. Moreover, if the system has higher objective usability it means that system that is easy to use (Venkatesh 2000, Venkatesh and Bala 2008). Several studies suggested that usability is a determinant of PEOU (Venkatesh 2000, Venkatesh and Bala 2008, Scholtz, Mahmud et al. 2016).

Regarding study limitations, our sample is not representative of the entire older population since we used a convenience sample. Therefore, findings cannot be widely generalizable. Moreover, the population sample is more homogenous than the wider population on the common factors, possibly leading to attenuation in correlations and/or erroneous correlations among variables (Fabrigar, Wegener et al. 1999, Wolf, Harrington et al. 2013). Although we have a minimum sample size adequate for the estimation method (>100 participants), the structural equation modeling is a large-sample technique (Kyriazos 2018). Therefore, future studies should have a larger and more heterogeneous sample to obtain sufficiently accurate estimates, even that the present study had a larger sample size compared to previous ones (Vooijs, Alpay et al. 2014, Mercer, Giangregorio et al. 2016, Farina and Lowry 2017, Puri, Kim et al. 2017). A further limitation is that the user experience was assessed for a specific wearable activity tracker (Xiaomi Mi Band 2®); therefore, it is not representative of the full range of devices currently available on the market. Moreover, the testing period was limited to 15 days. Short-term technology acceptance may not be indicative of long-term acceptance as research indicates that activity trackers tend to drop after the first few weeks (Puri, Kim et al. 2017, Shin, Jarrahi et al. 2019), with also short-time frames making it difficult to determine the impact of the novelty effect (defined as a person’s subjective "first responses to a technology, not the patterns of usage that will persist over time as the product ceases to be new"(Sung, Christensen et al. 2009)). Moreover, research suggests that the declining novelty effect could be a reason for many activity tracker users discontinuing their use. Recently, Shin et al. (2018) explored the effect of novelty in the early stages (<3 months) of activity tracker adoption, as well as the motivation factors for sustained activity tracker use for the long term (> 6 months). Findings reveal that the use beyond the novelty period is determined by intrinsic and extrinsic motivations (Shin, Feng et al. 2019). Finally, we selected the SUS for the usability evaluation since it is the most widely used questionnaire to measure perceived usability; however, this instrument does not comprise all of the concepts regarding usability. For instance, there are several different standards (e.g., ISO-9241-11, ISO/IEC 9126) and conceptual models to evaluate usability. Shackel (1991) reported on the four important characteristics of usability –namely, effectiveness, learnability, flexibility, and attitude–, and Nielsen Model (1993) gave five sub-attributes of usability –namely, learnability, efficiency, memorability, errors, and satisfaction [1, 2]. Therefore, there still a need for future studies comprising key dimensions of usability.

Concluding, while there is a pressing need for studies to include other devices currently on the market and evaluate longer-term use, our study extended on the existing research providing valuable insight into the field of wearable activity trackers in older adults. First, a significant contribution of this work was to demonstrate the relevance of usability as an important factor influencing user satisfaction, which probably has an impact on technology acceptance and in the intention to use activity trackers. However, we were not able to predict BI in our structural model. Furthermore, our results emphasize the need to consider strategies to minimize the usability barriers to technology adoption in older adults. In addition, system designers should provide systems that address these concerns, and the researchers must ensure that selected systems adequately address the usability issues to be effectively implemented in clinical and research settings. Second, our study investigated the impact of user characteristics as moderating factors influencing the relationship between usability and user satisfaction and found that depression symptoms have a significant influence on older adults' perception of using technology. However, other individual differences/personal user characteristics should be examined, and the identified moderating effects should be taken into consideration when implementing strategies trying to promote technology adoption. Finally, our results suggested that the Xiaomi Mi Band 2® is a suitable wearable activity tracker for older adults to use in a real-life context.

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6. Authors' Contributions

CD: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

PSC: Formal analysis, Methodology, Writing – review & editing.

NCS: Funding acquisition, Supervision, Writing – review & editing.

JMP: Funding acquisition, Supervision, Writing – review & editing.

All authors reviewed and approved the final version of the manuscript.

7. Conflicts of Interest

None declared.

8. Abbreviations

CANX: computer anxiety

CFA: Confirmatory factor analysis

CFI: Comparative Fit Index

GDS: Geriatric Depression Scale

GFI: Goodness of Fit Index

KMO: Kaiser-Meyer-Olkin Measure

M: Mean

MMSE: Mini-Mental State Examination

PA: Physical activity

PEC: Perceptions of external control

PEOU: Perceived ease of use

PU: Perceived usefulness

RMSEA: Root Mean Squared Error of Approximation

SD: Standard deviation

SRMR: Standardized Root Mean Squared Residual

SUS: System Usability Scale

TAM 3: Technology Acceptance Model

TLI: Tucker–Lewis Index

TRA: Theory of Reasoned Action

USEQ: User Satisfaction Evaluation Questionnaire

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10. Supplementary material

Supplementary Table 1. Measurement items of TAM 3.

Construct	**Code**	**Question**
Perceived Ease of Use	PEOU 1	My interaction with the system is clear and understandable.
	PEOU 2	Interacting with the system does not require a lot of my mental effort.
	PEOU 3	I find the system to be easy to use.
	PEOU 4	I find it easy to get the system to do what I want it to do.
Perceptions of External control	PEC1	I have the resources necessary to use the system.
	PEC2	The system is not compatible with other systems I use.
Computer Anxiety	CANX1	Computers do not scare me at all.
	CANX2	Working with a computer makes me nervous.
	CANX3	Computers make me feel uncomfortable.
Behavioral intention	BI	Assuming I had access to the system, I intend to use it. Given that I had access to the system, I predict that I would use it.
Use	USE	On average, how much time do you spend on the system each day?

Supplementary Table 2. Measurement items of USEQ.

Code	**Question**
USEQ1	Did you enjoy your experience with the system?
USEQ2	Were you successful using the system?
USEQ3	Were you able to control the system?
USEQ4	Is the information provided by the system clear?
USEQ5	Did you feel discomfort during your experience with the system?
USEQ6	Do you think that this system will be helpful for your rehabilitation?

Supplementary Table 3. Measurement items of SUS.

Code	Question
SUS1	I think that I would like to use this system frequently.
SUS2	I found the system unnecessarily complex.
SUS3	I thought the system was easy to use.
SUS4	I think that I would need the support of a technical person to be able to use this system.
SUS5	I found the various functions in this system were well integrated.
SUS6	I thought there was too much inconsistency in this system.
SUS7	I would imagine that most people would learn to use this system very quickly.
SUS8	I found the system very cumbersome to use.
SUS9	I felt very confident using the System.
SUS10	I needed to learn a lot of things before I could get going with this system.

CHAPTER IV

Effects of physical activity on brain function and structure in older adults: a systematic review

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Effects of physical activity on brain function and structure in older adults: a systematic review.

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1. Highlights

- Physical activity effects are regionally specific to brain regions vulnerable to dementia.
- Functional magnetic resonance imaging studies suggest a positive relationship between physical activity and cognitive performance.
- Protective effects of physical activity appear to be greater in healthy older adults at genetic risk for dementia.
- The high heterogeneity in PA assessment limits the establishment of PA recommendations.

1. Abstract

Despite the increasing evidence that physical activity (PA) contributes to brain health in older individuals, impacting on both brain structure and function, this relationship is not yet well established. To explore this association, a systematic literature search was performed using PubMed, Scopus, and Web of Science, adhering to PRISMA guidelines. A total of 32 studies met the eligibility criteria: 24 cross-sectional and 8 longitudinal. Results from structural MRI studies showed that PA was associated with larger brain volumes (less brain atrophy) specifically in brain regions vulnerable to dementia, comprising the hippocampus, temporal, and frontal regions. Furthermore, fMRI studies showed greater task-relevant activity in brain areas recruited in executive function and memory tasks. However, the dose-response relationship is unclear due to the high variability in PA measures. Further research using objective PA measures is needed to better understand which PA intensity, frequency, and duration, as well as PA type, has the greatest protective effect on brain health. Findings highlight the importance of PA in both cognitive decline and dementia prevention.

Keywords

Exercise; accelerometry; seniors; elderly; brain ageing; neuroimaging.

2. Introduction

Normal aging typically leads to global brain atrophy, modifications in brain functional responses, and cognitive decline (C. J. Boraxbekk, Salami, Wahlin, & Nyberg, 2016). Nevertheless, it has high inter-individual variability and appears to be dependent, for instance, on lifestyle habits (Bittner, Jockwitz, & Muhleisen, 2019). Among these, physical activity (PA) represents a promising non-pharmacological interventional approach to maintain, delay and/or improve brain structure and function throughout life (Benedict et al., 2013; Bittner et al., 2019; Sexton et al., 2016). Moreover, it is easily accessible, safe, and potentially cost-effective (Haeger, Costa, Schulz, & Reetz, 2019; Voss et al., 2016).

Structural and functional magnetic resonance imaging (MRI) have been used to assess the link between PA and brain structure and function in older adults (Halloway, Wilbur, Schoeny, & Arfanakis, 2017; Hayes, Hayes, Cadden, & Verfaellie, 2013). In structural MRI studies, higher levels have been associated with greater brain grey matter (GM) volumes (Kirk I. Erickson, Leckie, & Weinstein, 2014) in brain regions including the hippocampus (Kirk I. Erickson et al., 2014; Firth et al., 2018) and prefrontal cortex (Kirk I. Erickson et al., 2014), and preserved white matter (WM) integrity (Tian et al., 2015), reduced severity of WM lesions, and improvements in WM microstructure (Sexton et al., 2016; Tian et al., 2015). Notably, these structural changes are often associated with improved cognitive performance and reported to be severely affected in dementia Chieffi et al., 2017). Similarly, functional MRI (fMRI) research has shown that PA has a positive relationship with the functional connectivity (FC) of several cortical networks, with the strongest effect in the default mode network (DMN) (C.-J. Boraxbekk, Salami, Wåhlin, & Nyberg, 2016; Voss et al., 2016). Although fMRI is often considered the gold standard for the assessment of brain activity, other neuroimaging techniques such as functional near-infrared spectroscopy (fNIRS), positron-emission tomography (PET), and electroencephalography (EEG), have also been used (Herold, Wiegel, Scholkmann, & Müller, 2018). For instance, acute exercise was associated with improved performance in executive tasks in fNIRS (Ji, Feng, Mei, Li, & Zhang, 2019) and improved fine motor control performance in an EEG study (Hübner, Godde, & Voelcker-Rehage, 2018). Nonetheless, most of the studies examining the effects of PA and brain health have, thus far, relied on subjective measures (Burzynska et al., 2014; Kirk I. Erickson et al., 2014), such as self-report questionnaires, whose validity in measuring the type, intensity, and duration of the activities of daily living is limited (Kirk I. Erickson et al., 2014; Tian et al., 2015). A precise measurement of PA is essential to advance our knowledge of PA effects in brain structure and function. In fact, there are many different methods available to measure PA, including behavioral observations, questionnaires, diaries, direct/indirect calorimetry, and wearable sensors (Skender et al., 2016); with, for instance, the latter providing an objective and precise assessment of everyday activities including non-exercise lifestyle activities and sedentary behavior measures Burzynska et al., 2014; Kirk I. Erickson et al., 2014).

In this context, recent systematic reviews have examined the relationship between PA and brain structure and function in older adults (Chen et al., 2020; Haeger et al., 2019; Sexton et al., 2016). Haeger et al. (2019) evaluated the effects of PA on brain structure and function in mild cognitive impairment (MCI) and Alzheimer's disease (AD) patients when compared to cognitively healthy individuals in randomized, non-randomized controlled, and cohort study designs. Results indicate that the effects of aerobic exercise and fitness seem to occur mainly in brain structures sensitive to neurodegeneration, including frontal, temporal, and parietal regions (Haeger et al., 2019). Chen et al. (2020) specifically examined the effects of randomized controlled exercise interventions on brain structure and function in cognitively intact older adults and explored the underlying relationships based on characteristics of exercise training (i.e., frequency, intensity, time, type, volume, and progression). The findings indicate that older adults involved in exercise training may have benefits in brain health in a dose-dependent manner (Chen et al., 2020). Still, despite a growing number of observational studies, no systematic review on the overall impact of PA on healthy brain aging has been conducted, with only a systematic review partially addressing the issue. Analyzing cross-sectional and longitudinal MRI studies, Sexton et al. (2016) explored the associations between PA and physical fitness in WM in brain aging. The authors found that higher levels of PA were associated with greater WM volumes, reduced volume or severity of WM lesions, or improved measures of WM microstructure. However, several negative findings were also found (Sexton et al., 2016).

The present systematic review is, to the best of our knowledge, the first to explore observational cross-sectional and longitudinal neuroimaging MRI studies that have examined the relationship between PA and brain structure and function in older adults without cognitive or neuropathological disease. This study aims to answer the following questions: i) are PA levels associated with brain structure and function in older individuals without cognitive or neuropathological disease; ii) what structural and functional brain changes are associated with PA; and, if associated, iii) what are the PA recommendations for brain health improvement.

3. Methods

The systematic review was performed according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) recommendations (Liberati et al., 2009; Moher, Liberati, Tetzlaff, & Altman, 2009). The review protocol was not registered.

Eligibility criteria

Studies were included if met the following criteria:

a. Studies with original data. Conference abstracts, reviews, and book chapters were excluded. No limits were applied to publication date;
b. Cross-sectional or longitudinal observational studies. Experimental studies were excluded;
c. Published in peer-reviewed and English language journals;
d. Conducted in humans;
e. Examined cognitively healthy older adults free from cognitive (dementia), psychiatric or neurological disorders, with population samples characterized as "older adults", "elders" or "senior", or age groups equal or above 60 years old. If studies comprised cohorts with disease, a "healthy control" group/sample must have been present. The same consideration was taken regarding age group, if younger adults it must also have comprised an "older" adult cohort;
f. Assessed the level of PA by self-reported questionnaires or accelerometry. Due to the high variability in methods used to assess PA, studies with other methods were excluded to facilitate comparisons between results that are directly comparable;
g. Assessed the brain structure and/or function as measured by MRI;
h. Examined a direct association between PA and MRI measures;
i. Comprised (at least) one cognitive screening/assessment test.

Information sources and search

The literature search was performed using Pubmed, Web of Science, and Scopus databases. The search was conducted on the 23rd of July 2019 by the author CD. The search strategy was constructed based on the PICO framework (population (P), intervention (I), comparison (C), and outcome (O)). Table 1 provides a detailed description of the electronic search strategy in Pubmed. Similar terms were used for the other databases. Filters for Humans and English language were used in the Pubmed search.

Table 1. Electronic search strategy.

Boolean Builder	Search terms
	Exercise OR "Physical Activity" OR "Physical Exercise" OR "Physical Training" OR "Exercise Training" OR Aerobic OR Fitness
AND	Brain OR "Gray Matter" OR "White Matter" OR Hippocampus OR Hippocamp*
AND	"Magnetic Resonance Imaging" OR MRI OR fMRI OR "Functional MRI" OR Neuroimaging
AND	Aged OR Older OR Old OR Elderly OR Age

Study selection

All studies were first screened based on title and abstract and, subsequently, the selected full-text publications were systematically reviewed. Uncertainty about eligibility assessment was resolved by discussion and consensus among all the authors.

Data collection process

All relevant information from eligible studies was collected using a data extraction sheet based on data items in a previous review article (Sexton et al., 2016). In case of uncertainty, the results were discussed among the authors. Duplicate publications and studies with overlapping samples were carefully analyzed to avoid double counting the same data.

Data items

The following data were extracted from the eligible studies: (i) study design (cross-sectional or longitudinal); (ii) participant demographics (sample size, mean age, number of female participants); (iii) PA assessment (questionnaires or accelerometry); (iv) neuroimaging assessment (GM structure, WM structure, brain function, and functional connectivity); and (v) findings.

Risk of bias in individual studies

The risk of bias of the eligible studies was assessed through The Joanna Briggs Institute critical appraisal checklist (Joanna Briggs Institute, 2017). This checklist provides information about the methodological quality of a study regarding the possibility of bias in its design, conduct, and analysis. The following items were evaluated: Q1 "Were the criteria for inclusion in the sample clearly defined?" Q2 "Were the study subjects and the setting described in detail?" Q3 "Was the exposure measured in a valid and reliable way?" Q4 "Were objective, standard criteria used for measurement of the condition?" Q5 "Were confounding factors identified?" Q6 "Were strategies to deal with confounding factors stated?" Q7 "Were the outcomes measured in a valid and reliable way?" Q8 "Was an appropriate statistical analysis used?". Possible responses for each question include: "Yes"," No", "Unclear", and "Not Applicable". An overall quality score was decided based on the number of answers scored as "No" and/or "Unclear": Good: 0–1; Fair: 2–3; Poor: 4–5; Very Poor: 6 – 8.

4. Results

The literature search identified 1759 studies after duplicates removal. A total of 1583 studies were excluded based on title and abstract screening. Full texts of the remaining 176 studies were examined in detail accounting for the inclusion criteria. From those, 32 studies met the inclusion criteria. Details are outlined in the PRISMA flow diagram of the selection process (Figure 1).

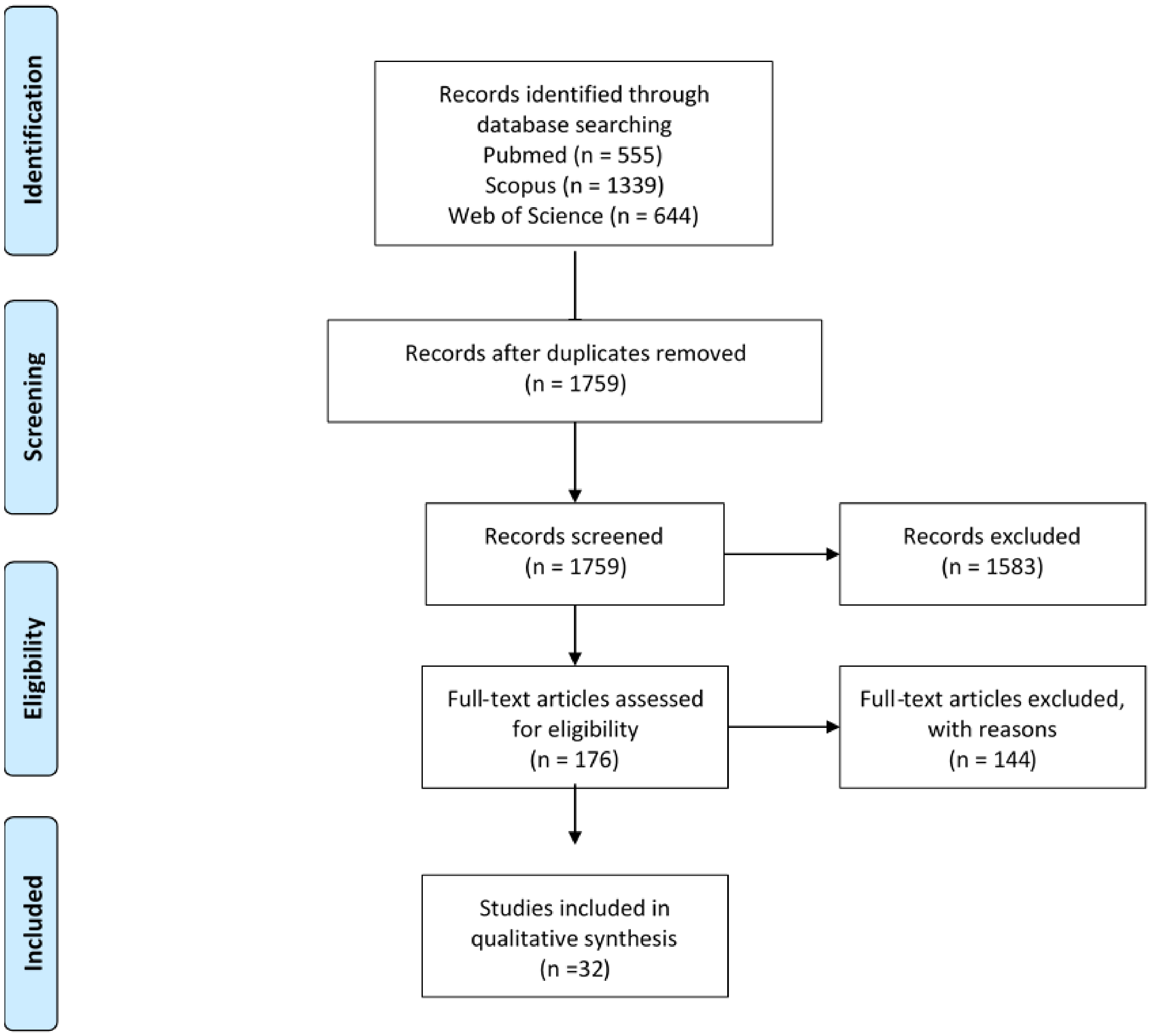

Figure 1. PRISMA Flow diagram describing the study selection process [adapted from Liberati, Altman et al. 2009, Moher, Liberati et al. 2009)].

Study characteristics

A total of 32 original studies met the eligibility criteria: 24 cross-sectional and 8 longitudinal studies (Figure 2).

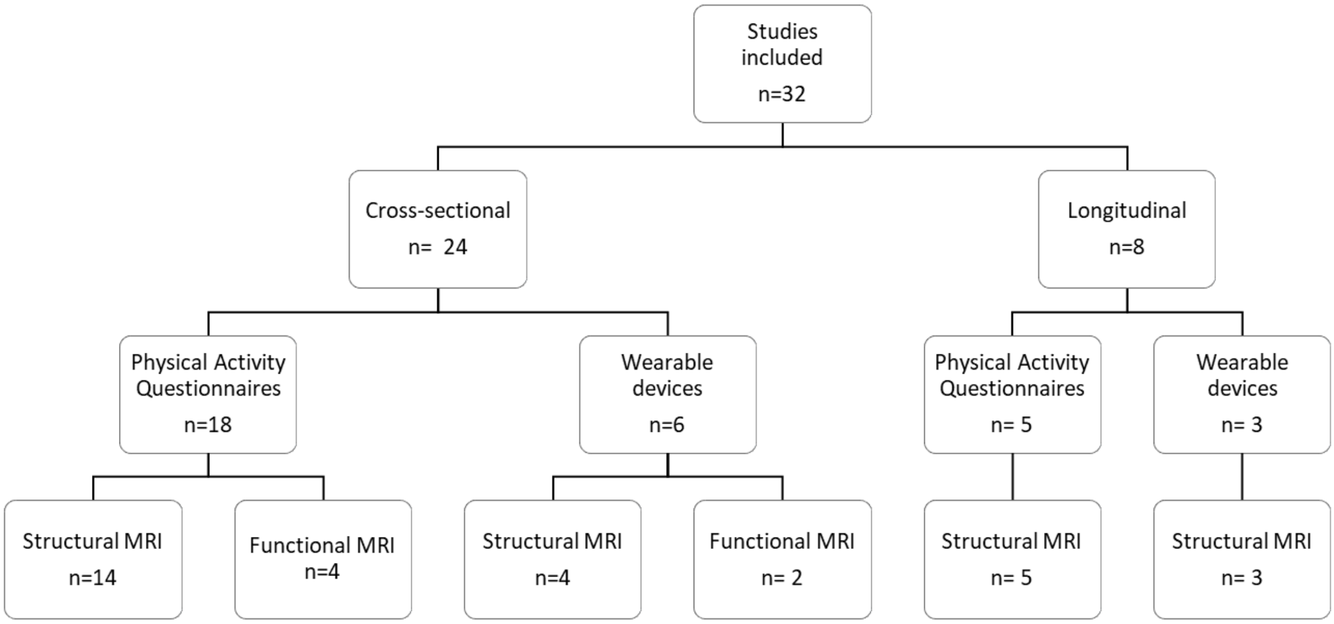

Figure 2. Summary of the selected studies included in the systematic review.

The identified studies were published between 2007 and 2019. In 30 studies (94 % of the studies) the proportion of female participants was higher than males; with, a few studies having either more males than females (Corlier et al., 2018; Kharabian Masouleh et al., 2018; Lamont, Mortby, Anstey, Sachdev, & Cherbuin, 2014; Lee et al., 2016; Young, Dowell, Watt, Tabet, & Rusted, 2016) or equal distribution (Arenaza-Urquijo et al., 2017; McGregor et al., 2011; Thielen et al., 2016). Eighteen studies had a sample size inferior to 100 participants, with 6 having less than 50 participants (Kimura, Yasunaga, & Wang, 2013; McGregor et al., 2011; Siddarth et al., 2018; Thielen et al., 2016; Zlatar et al., 2015; Zlatar et al., 2013).

Among those that used a self-report measure of PA (72 % of studies, n = 23), the Minnesota Leisure Time Physical Activity Questionnaire (MLTPAQ) was the most used questionnaire (26 % of studies, n = 6) followed by The International Physical Activity Questionnaire (IPAQ) (22 % of studies, n = 5). Of the included studies, only 28 % (n = 9) evaluated PA by accelerometry. In longitudinal studies, the mean follow-up time was 6.9 ± 4.6 years, with a minimum follow-up time of 12 months and a maximum of 13 years. Regarding global cognition assessment, the Mini Mental State Examination (MMSE) was used in most studies (53 % of studies, n = 17). Several works used a set of neuropsychological tests, including assessments of memory, attention, language, executive function, and visuo-spatial functioning. The evaluation of depression or anxiety scores was also considered in several studies.

Diffusion-tensor imaging (DTI) was used in 6 of the included studies (Best et al., 2017; Burzynska et al., 2014; Kim et al., 2016; Smith et al., 2016; Tian et al., 2014; Young et al., 2016). fMRI studies used semantic (Smith et al., 2011), episodic memory (Thielen et al., 2016), semantic fluency (Zlatar et al., 2015), motor task (McGregor et al., 2011), and task-switching reaction time (Kimura et al., 2013) tasks, and evaluated the FC of the resting state networks (Voss et al., 2016). Figure 3 shows the structural brain regions affected by PA in 26 of the included works. Effects of PA were reported in several brain regions, including hippocampus (n = 9), parietal lobe (n = 4), temporal lobe (n = 6), and frontal lobe (n = 9) (Figure 3). However, 4 reported no significant results (Cho et al., 2014; Kharabian Masouleh et al., 2018; Voss et al., 2016; Young et al., 2016) and 2 reported only significant results for women but not men (V. R. Varma, Chuang, Harris, Tan, & Carlson, 2015; Vijay R. Varma, Tang, & Carlson, 2016). Of note, some of the studies reported effects in more than one brain region.

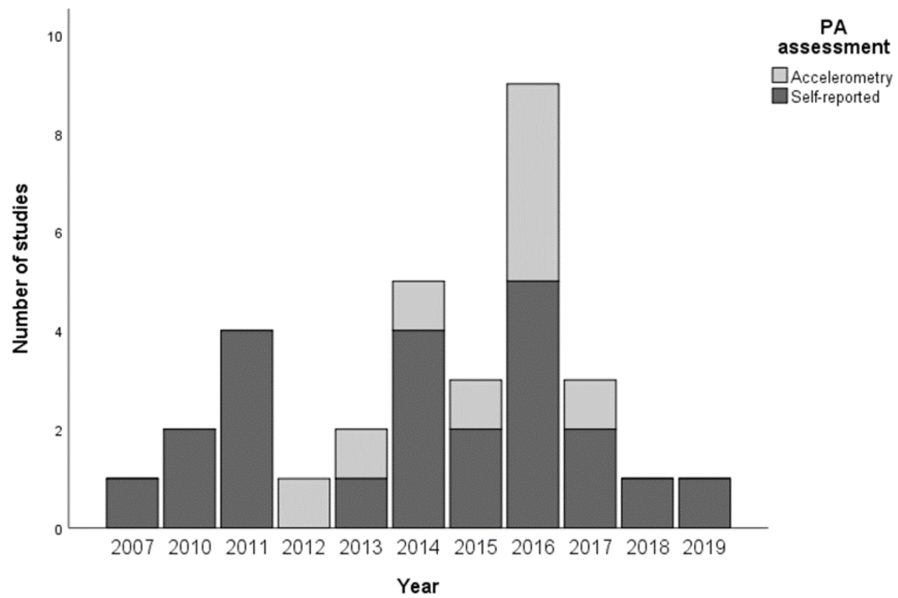

Figure. 3. Distribution of brain regions showing increased volume associated with PA in cross-sectional and longitudinal studies (n = 26). Note that some of the studies reported effect in more than one brain region.

Cross-sectional studies

Structural MRI studies

A total of 18 cross-sectional studies examined the relationship between brain structure and PA. From those, 14 used self-reported questionnaires (Table 2) and 4 measured PA by accelerometry (Table 3).

Table 2. Summary of cross-sectional studies reporting the effects of physical activity measured by self-reported questionnaires on brain structure.

Study	Participants groups	Sample size	Mean age ± SD	Number of females	Cognitive screening test	PA assessment	Neuroimaging assessment	Findings
Floel et al. (2010)	No groups	75	60.5±6.9	47	MMSE AVLT	Freiburg Questionnaire of physical activity	GM volume	Higher levels of PA were associated with increased cerebral GM volume in prefrontal and cingulate cortex.

Bugg et al. (2011)	Low Exercise	24	68.9 ± 7.4	18	CDR	Historical Physical Activity questionnaire (past 10 years)	GM and WM volume	Significant age-related atrophy of medial temporal for the low exercise group, but not for the high exercise group. Higher levels of exercise engagement were related to larger global, superior frontal cortex, and pericalcarine cortex volume.
	High Exercise	28	69.1 ± 6.1	19				
Ho et al. (2011)	PA level: Q1	45	78.0 ± 3.5	28	3MSE	MLTPAQ	GM and WM volumes	Greater PA was associated with ~2-

	Q2	45	77.4 ± 4.0	26				2.5% greater volumes in the WM of the corona radiata extending into the parietal-occipital junction.
	Q3	46	78.4 ± 3.8	29				
	Q4	45	78.2 ± 3.8	28				
	Q5	45	77.5 ± 2.6	20				
Brown et al. (2014)	BDNF Val/Val homozygotes	78	71.3 ±7.1	42	MMSE GDS CVLT-II RCFT D-KEFS verbal fluency BNT WTAR	IPAQ	GM volume	Higher levels of PA were associated with larger hippocampal volumes for all participants.
	BDNF Met carriers	36	72.4±7.0	20				Higher PA was associated with larger hippocampal and temporal lobe volumes in the

					Stroop RCFT			Val/Valhomozygotes group. Higher levels of PA were associated with smaller temporal lobe volume in the Met carriers group.
Lamont et al. (2014)	No groups	317	66.48 ± 1.43	145	MMSE BPHQ SDMT TMT-B DSB CVLT	Self-report Hours of average weekly PA (METs)	GM volume and surface area	Higher PA was associated width of the left superior frontal sulcus and right central Sulcus.

					STW			
Boyle at al. (2015)	Healthy controls	724	74.1 ± 4.4	562	3MSE BVRT DSST CES-D IQ-CODE	MLTPAQ	GM volume	In healthy controls the parietal lobe was significantly associated with PA, but not across the whole brain volume.
	MCI	135						
	AD	104						
Zlatar et al. (2015)	No groups	29	68.38 ± 5.99	Not reported	MMSE HVLT Stroop WAIS	Modified LTEQ	GM density (GMd)	PA was correlated with increased GMd in occipito-temporal, left perisylvian, and frontal regions. PA was associated with GMd in the left

								hippocampus.
Kim et al. (2016)	PA level: Q1	19	66.7 ± 5.4	14	K-MMSE GDS CANTAB	IPAQ	Intracerebral volume and structural connectivity	Higher intracerebral volume in the Q4 group. Higher regional nodal strength and local efficiency in middle frontal gyri, inferior parietal lobules, right superior/middle temporal gyrus in the Q4 group.
	Q2	19	66.8 ± 5.5	16				
	Q3	19	67.3 ± 4.0	12				
	Q4	19	68.2 ± 5.0	11				
Lee et al. (2016)	PA Longer duration	681	64.1 ± 6.5	321	MMSE	IPAQ-7	GM thickness	Longer duration of exercise, but not the frequency or intensity,

	PA Shorter duration	1161	63.7 ± 7.2	537				was correlated with the increased cortical thickness in the dorsolateral prefrontal cortex, precuneus, left postcentral gyrus, and inferior parietal regions.
Smith et al. (2016)	Groups base on PA level and presence of APOE-ε4: Low Risk/High PA	21	76.0 ± 4.7	15	MMSE 2DRS-2 Rey AVLT GDS	SBAS	WM tract integrity	Greater levels of PA were associated with greater FA and lower MD and RD in low risk groups (opposite pattern for high risk groups).
	Low Risk/Low PA	33	73.5 ± 4.7	26				Greater FA and lower

	High Risk/High PA	14	73.1 ± 4.4	15				MD and RD in High Risk/Low PA group compared to High Risk/High PA group.
	High Risk Low PA	14	70.0 ± 4.2	9				
Arenaza et al. (2017)	No groups	45	71.9 ± 6.6	23	MMSE	MAQ French version	GM volume	PA was associated with increased insular cortex, prefrontal cortex and motor area, and hippocampal head volume.
Hashimoto et al. (2017)	No groups	213	68.9 ± 7.5	114	MMSE RBMT	Modified Baecke Questionnaire	GM and hippocampal volume	Hippocampal atrophy was associated with leisure-time physical inactivity.
Kharabian et al.	No groups	616	69 ± 5	258	CERAD	IPAQ-SF	GM-networks	No independent significant association

(2018)		(516 with PA information)			CES-D			between PA and GM networks were found.
Torres et al. (2019)	Active group without a psychiatric history	20	62.1 ± 7.1	13	MMSE SCID	LTPAQ	WMHs volume and Intracranial volume	Leisure-time physical activity was not significantly associated with WMHs.
	Less active group without a psychiatric history	13	64.0 ± 6.7	7				
	Less active group with psychiatric history	14	62.8 ± 7.1	9				

2DRS-2: Mattis Dementia Rating Scale 2, 3MSE: Modified Mini Mental State Examination, AD: Alzheimer's disease, BDNF: Brain-derived neurotrophic factor, BNT: 30-item Boston Naming Test, BPHQ: Brief patient health questionnaire, BVRT: Benton Visual Retention Test, CANTAB: Cambridge Neuropsychological Test Automated Battery, CDR: Clinical Dementia Rating, CERAD: The consortium to establish a registry for Alzheimer's disease, CES-D: Center for Epidemiologic Studies Depression Scale, CVLT: California Verbal Learning Test, D-KEFS: Delis-Kaplan Executive Function System, DSB: Digit Span Backwards, DSST: Digit Symbol Substitution Test, GDS: Geriatric Depression Scale, GM: Grey matter, IPAQ: The International Physical Activity Questionnaire, IPAQ-SF: The International Physical Activity Questionnaire-Short Form, IQ–CODE: The Informant Questionnaire on Cognitive Decline in the Elderly, K-MMSE: Korean version of the Mini Mental Status Examination, LTPAQ: Lifetime Total Physical Activity Questionnaire, MAQ: Modifiable Activity Questionnaire, METs: metabolic equivalent, MLTEQ: Leisure-Time Exercise Questionnaire, MLTPAQ: Minnesota Leisure Time Physical Activity Questionnaire, MMSE: Mini Mental Status Examination, RAVLT: Rey Auditory Verbal Learning Test, RBMT: Rivermead Behavioral Memory Test, RCFT: Rey Complex Figure Test, SBAS: Stanford Brief Activity Survey, SCID: Structured Clinical Interview for DSM-IV Axis I Disorders, SDMT: Symbol Digit Modalities Test, STW: Spot-the-Word task, TMT-B: Trail Making Test, WAIS: Wechsler Abbreviated Scale of Intelligence, WM: White matter, WMH: White matter hyperintensities, WTAR: Wechsler Test of Adult Reading WAIS – III.

Table 3. Summary of cross-sectional studies reporting the effects of physical activity measured by accelerometry on brain structure.

Study	Participants groups	Sample size	Mean age ± SD	Number of females	Cognitive screening test	PA assessment	Neuroimaging assessment	Findings
Burzynska et al. (2014)	No groups	88	65±4	55	MMSE TICS-M GDS-15	GT3× ActiGraph Tri-axial accelerometer (7 days)	WMH volume and WM integrity	Greater MV-PA was associated to a lower volume of WMH. Greater light PA was associated with higher FA in the temporal lobe. Sedentary behavior was inversely associated with

								FA in the parahippocampal.
Varma et al. (2015)	No groups	92	67.3 ± 6.1	64	MMSE	SAM step activity monitor (3-7 days)	GM volume	Greater amount, duration, and frequency of total daily walking activity were associated with larger hippocampal volume in women, but not men.
Dougherty et al. (2016)	Sample meeting PAR	29	63.5 ± 4.9	18	MMSE	GT3× ActiGraph Tri-axial accelerometer (7 days)	GM volume	Greater inferior and anterior temporal lobe volumes in meeting PAR group.
	Sample not meeting PAR	62	64.4 ± 6.2	42				
Varma et al. (2016)	No groups	90	67.3 ± 6.0	63	MMSE	SAM step activity monitor (3-7	Surface-based regional shape	Total walking activity was associated with larger

						days) + CHAMPS questionnaire		hippocampal surface area in women but not men.

CHAMPS: Community Healthy Activities Model Program for Seniors, FA: Fractional anisotropy, GDS: Geriatric Depression Scale, MMSE: Mini Mental Status Examination, MV-PA: Moderate to vigorous activity, TICS: The Telephone Interview for Cognitive Status, WM: White matter, WMH: white Matter hyperintensities.

Brain regions

The most consistent association between PA and brain structure across the studies point for a positive impact of PA on frontal and temporal regions, including the hippocampus. Using a questionnaire that estimates exercise engagement over the past 10 years, Bugg et al. (2011) found that higher levels of exercise engagement were correlated with a larger superior frontal cortex and pericalcarine cortex volume (Bugg & Head, 2011). Similarly, Floel et al. (2010) describe more preserved GM in the prefrontal and cingulate cortex. This study has the particularity that the authors additionally showed that higher PA is associated with better memory functions and higher levels of neurotrophins, although the exact link needs to be further elucidated in larger samples of the general population (Floel et al., 2010). Moreover, Bugg et al. (2011) also observed significant age-related atrophy in the medial temporal lobe in older adults who engaged in low levels of exercise compared to the ones who engaged in high levels of exercise. These findings highlight the efficacy of PA to maintain the medial temporal lobe integrity in older adults. However, results were based on relatively small sample size (n = 52). Thus, future research with larger sample sizes are needed to provide sufficient power to detect any potentially moderating effects in these regions (Bugg & Head, 2011). Importantly, temporal lobe atrophy has been associated with aging, and this atrophy can predict cognitive decline to AD (Dougherty et al., 2016). Dougherty et al. (2016) examined temporal lobe volumetric differences between older adults categorized as having met PA recommendations and those who were insufficiently active (Dougherty et al., 2016). Recommendations for healthy older adults are the same as for adults but a different definition of aerobic intensity more appropriate for the former because their fitness levels are possibly low. Therefore, the recommendation is 150 min of moderate-intensity, or 75 min of vigorous-intensity, or an equivalent combination of moderate and vigorous PA per week, but with the aerobic intensity defined as relative to fitness, in the manner of an exercise prescription (Nelson et al., 2007). The study showed greater inferior and anterior temporal lobe volume in participants who engaged in current recommended levels of PA compared to those who did not meet the recommendations. Curiously, the observed effect size for the inferior temporal lobe was reinforced when the sample was restricted to participants at genetic risk of AD but without AD. The findings suggest that participation in regular PA at or above recommended levels may mitigate the detrimental effects of aging on temporal lobe volume particularly in individuals with a familial risk of AD (Dougherty et al., 2016).

Additionally, two studies were identified that report an association between PA and brain structure in the parietal lobe. Boyle at al. (2015) explored the associations between self-reported PA, BMI (body mass index) and regional brain volumes in a cohort including people with MCI and AD. In healthy controls, the parietal lobe was significantly associated with PA. The authors also found that BMI is a strong predictor of brain structure (Boyle et al., 2015). The second study, considering BMI as a determinant factor in the relationship between PA and brain structure, indicates that higher PA associates with ~2–2.5% greater average tissue volumes in the WM of the corona radiata extending into the parietal-occipital junction (Ho et al., 2011).

Hippocampus

Hippocampal atrophy is the most recognized structural AD neuroimaging biomarker (Arenaza-Urquijo et al., 2017; Hashimoto et al., 2017; V. R. Varma et al., 2015). Emerging evidence suggests that PA may attenuate the age-related decline in hippocampal volume (Brown et al., 2014). Varma et al. (2015) explored whether greater objectively measured daily walking activity was associated with larger hippocampal volume. Results showed that the amount, duration, and frequency of total daily walking activity were associated with larger hippocampal volume in women but not men. The finding was specific to the hippocampus, using the thalamus as control brain region. Furthermore, the relationship remained significant for low-intensity walking activity, independent of moderate- to vigorous-intensity activity (V. R. Varma et al., 2015). In another study, the same authors used objective and self-reported measures of daily walking activity and shape diffeomorphometry to explore sub-region specific hippocampal association with PA. Specifically in women, the objectively measured walking activity was associated mainly with larger surface areas of the subiculum in the hippocampus. The findings suggest that low-intensity walking activities (i.e., locomotion in everyday lifestyle activities), may be specifically associated with the subiculum subregion of the hippocampus. Interestingly, no significant correlation was observed between objective and self-reported measures in women (Vijay R. Varma et al., 2016). Of note, the studies from Varma et al. used the MMSE as a covariate in the analytic models which may account for the possibility of reverse causation. Moreover, the step activity monitor used was validated across a range of community-dwelling older adults. Although not differentiating among types of activities, the data obtained from the monitor included the frequency, duration, intensity of PA (light, moderate, vigorous, and moderate-to-vigorous), sedentary behavior, and caloric expenditure (wear time ranged from 3 to 7 days) (V. R. Varma et al., 2015; Vijay R. Varma et al., 2016).

The hippocampus is also essential for short- and long-term memory consolidation (Brown et al., 2014). Hashimoto et al. (2017) examined the relationship between PA, hippocampal atrophy, and memory function, in healthy older adults. The authors found that hippocampal atrophy and whole brain GM atrophy were associated with leisure-time physical inactivity. Furthermore, hippocampal atrophy was associated with cognitive and memory dysfunction. This study has the strength of including the evaluation of memory function (Rivermead Behavioral Memory Test, RBMT) in addition to the standard screening test MMSE (Hashimoto et al., 2017).

Currently, it is described that BDNF (Brain-derived neurotrophic factor) Val66Met polymorphism results in poorer episodic memory and reduced hippocampal volume in the preclinical stages of AD. Thus, Brown et al. (2014) explored the effect of the BDNF Val66Met gene on the relationship between PA and the volumes of the hippocampus, temporal lobe, and medial temporal lobe. The authors divided the cognitively healthy participants into two groups: BDNF Val/Val homozygotes and BDNF Met carriers. In Val/Val homozygotes participants, higher levels of PA were associated with larger hippocampal and temporal lobe volumes, while in Met carriers this was associated with smaller temporal lobe volume. Results indicate that PA may reduce age- and disease-related hippocampal and temporal lobe volume loss in Val/Val homozygotes. Despite these results, a larger sample size is required to further investigate the potential of genetic interactions in the relationship between PA and brain volume (Brown et al., 2014).

Arenaza et al. (2017) studied the effects of PA and cognitive activity during late adulthood in association with GM, with a special focus on the hippocampus. They used a hippocampus 3D surface mapping method and detected a positive association between PA and GM volume located in the anterior part of the hippocampus, mainly corresponding to CA1 and the subiculum. PA was associated with increased GM in the prefrontal, insular, and motor cortices. The results suggest that engagement in PA and cognitive activity in late adulthood may have specific regional associations with GM volume in AD vulnerable areas (Arenaza-Urquijo et al., 2017)

Lastly, Zlatar et al. (2015) using voxel-wise analyses observed that self-report PA correlated with increased GM density (GMd) in the left hippocampus and occipito-temporal, left perisylvian, and frontal regions. The authors also used an objective measure of aerobic fitness. Results showed that aerobic fitness and PA were associated with GMd in distinct and non-overlapping brain regions, but due small sample size (n = 29) the study should be interpreted with caution (Zlatar et al., 2015).

WM hyperintensities

Brain aging comprises several structural and functional changes. One of the most common is the appearance of lesions called WM hyperintensities (WMH) and degeneration of WM microstructure [17]. Since WMH increase with vascular risk factors and PA improves cardiovascular health, PA is a lifestyle factor that may attenuate the age-related progression of WMHs Moon et al., 2018; Raz, Yang, Dahle, & Land, 2012; Torres et al., 2019).

Burzynska et al. (2014) explored the associations of objectively measured sedentary behavior, light PA, and moderate-to-vigorous PA (MV-PA), with WMH volume and WM integrity. Results showed that greater PA was associated with lower WMH volume. Thus, the authors suggest that the mechanism underlying this association is the beneficial effect of the MV-PA on the cerebrovascular system. Furthermore, they found that the association between PA and WM microstructural integrity was region-specific: light PA was related to temporal WM, while sedentary behavior was related to lower integrity in the parahippocampal WM. These findings suggest that PA is associated with different aspects of WM health in intensity- and region-specific manner. However, the study sample was restricted to health in older low-fit, and low-active adults, which may limit the study conclusions (Burzynska et al., 2014).

Additionally, WMH has been associated with neuropsychiatric disorders, including depression and the risk of cognitive decline (Moon et al., 2018; Raz et al., 2012; Torres et al., 2019). Torres et al. (2019) explored the association between PA and WMHs while accounting for depression in cognitively intact older adults. Based on PA levels and psychiatric history, three participant groups were established: the active group without a psychiatric history, the less active group without a psychiatric history, and the less active group with a psychiatric history. Results showed no significant difference in WMH; neither between the more and less active groups without a psychiatric history, nor between the more active group without a psychiatric history and the less active group with a history of depression. Moreover, leisure-time activity was not associated with WMHs in cognitively intact adults [42]. One important limitation that should be noted is the small sample size (n = 47), which may limit the statistical differences among the three groups (Torres et al., 2019).

Cortical thickness

Aging is associated with reductions in cortical thickness, which is a promising marker of morphometric change in the brain during normal aging. One factor that seems to mitigate this age-related cortical atrophy is PA. Lee et al. (2016) found that a longer duration of PA, but not intensity or frequency, was associated with increased mean cortical thickness globally and in frontal regions. Moreover, the association of PA with cortical thinning had regional specificity in the bilateral dorsolateral prefrontal, precuneus, left postcentral, and inferior parietal regions. The authors also observed that a combination of PA with education had more protective effects on age-related cortical thinning than PA alone. This study has strengths that includes a large sample size (n = 1842) and sophisticated measurements of cortical thickness (Lee et al., 2016).

Structural brain networks

Structural brain networks change with age and are related to cognitive decline and neurodegenerative diseases. PA is a modifiable lifestyle factor that may reduce the risk for developing these pathologies (Kharabian Masouleh et al., 2018; Kim et al., 2016). Kim et al. (2016) compared the structural brain network properties and cognitive functions in older adults according to the level of PA in daily life. The regional nodal strength and local efficiency significantly increased in the higher PA group, which involved the bilateral middle frontal gyri, the inferior parietal lobules, and the right superior and middle temporal gyrus. Moreover, PA was associated with a better performance in speed processing and increased network connectivity of attention-related brain areas (Kim et al., 2016). On the other hand, Kharabian et al. (2018) explored the unique contribution of cardiovascular risk factors on GM networks. Considering the effect of PA, no independent significant associations with the GM networks were found (Kharabian Masouleh et al., 2018).

fMRI studies

A total of 6 studies examined the relationship between brain function and PA. From those, 4 studies measured PA by self-reported questionnaires (Table 4) and 2 measured PA by accelerometry (Table 5).

Table 4. Summary of cross-sectional studies reporting the effects of physical activity measured by self-reported questionnaires on brain function.

Study	Participants groups	Sample size	Mean age ± SD	Number of females	Cognitive screening test	PA assessment	Neuroimaging assessment	Findings
McGregor et al. (2011)	Physically active older (PAO)	12	68.2 ± 6.74	13	MMSE	LTEQ	BOLD response (motor task)	Lower BOLD response in the right primary motor cortex in PAO and young group compared to SO.
	Sedentary Older (SO)	12	70.64 ±7.5					
	Young	1	24.3 ± 2.86					

Smith et al. (2011)	Groups base on PA level and presence of APOE-ε4: Low Risk/High PA	17	74.3 ± 4.6	13	MMSE DRS-2 RAVLT GDS	SBAS	BOLD response (semantic memory task) and GM volume	Greater BOLD response (famous > unfamiliar faces) in medial frontal gyrus/supplementary motor area, left precentral gyrus, middle/superior frontal gyrus, left middle/inferior temporal gyrus/angular gyrus/supramarginal gyrus/precuneus in the physically active group compared to the physically inactive group.
	Low Risk/Low PA	17	73.3 ± 5.2	14				
	High Risk/High PA	17	70.7 ± 4.2	12				
	High Risk Low PA	17	72.9 ± 5.2	11				

								The effects of PA on task-related activation were more pronounced in APOE-ε4 carriers.
Zlatar et al. (2013)	Physically Active Older (PAO)	15	68.6 ± 6.77	8	MMSE	LTEQ	BOLD response (semantic fluency task)	Greater BOLD response in the right angular gyrus/lateral occipital cortex and left supramarginal gyrus in the SO compared to PAO group.
	Sedentary Older (SO)	12	69 ± 5.27	9				
	Young Adult (YA)	14	24.21 ± 4.81	4				
Thielen et al. (2016)	Aerobic (-)	16	61.19 ± 4.87	7	VLTM BVMT-R/PAL TMT-A	PASE	BOLD response (memory encoding task) and functional	Greater BOLD response in the left hippocampus in the aerobic (+) group.
	Aerobic (+)	16	59.75 ± 5.19	9				

					TMT-B IED COWAT		connectivity	Greater functional connectivity between mPFC and left thalamus/right hippocampus and insula in the aerobic (+) group.

APOE-ε4: apolipoproteinE-ε4, BVMT-R/PAL: Brief Visuospatial Memory Test-Revised and the Paired Associates Learning, COWAT: Controlled Oral Word Association Test, DRS-2: Mattis Dementia Rating Scale 2, fMRI: Functional magnetic resonance imaging, GDS: Geriatric Depression Scale, IED: Extra-dimensional Shift, LTEQ: Leisure-Time Exercise Questionnaire, MMSE: Mini Mental Status Examination, PAO: Physically Active Older, PASE: Physical Activity Scale for the Elderly, AVLT: Rey Auditory Verbal Learning Test, SBAS: Stanford Brief Activity Survey, SO: Sedentary Older, TMT: Trail Making Test, VLTM: Verbal Long-term memory, YA: Young Adult.

Table 5. Summary of cross-sectional studies reporting the effects of physical activity measured by accelerometry on brain function.

Study	Participants groups	Sample size	Mean age ± SD	Number of females	Cognitive screening test	PA assessment	Neuroimaging assessment	Findings
Kimura et al. (2013)	Short brisk walking group	21	70.9 ± 4.1	9	MMSE	Kenz Lifecorder EX accelerometer (3 months)	BOLD response (task-switching reaction time)	Greater BOLD response in the in the left prefrontal and parietal regions in the Short brisk walking group. Greater BOLD response in the dorsolateral prefrontal cortex in the Long brisk walking group.
	Long brisk walking group	22	71.3 ±3.5	14				
Voss et al.	Older adult lower fit	47	64.6 ±3.7	47	MMSE TICS-M	GT3× ActiGraph	Functional connectivity of resting state networks	Positive association between fitness and

(2016)	group (LF)				GDS-15	Tri-axial accelerometer (7 days)		default-mode and dorsal attention within-network connectivity.
	Older adult higher fit (HF)	47	64.5 ± 4.1	47				Negative association between fitness and connectivity between default-mode and dorsal attention network.
	Young	36	22.1 ± 3.0	36				Greater connectivity between default-mode and amygdala/ hippocampus/ ventromedial prefrontal cortex and lower

								connectivity between default-mode and precentral gyrus/postcentral gyrus/supplementary motor cortex in HF compared to the LF group.

GDS: Geriatric Depression Scale, HF: Higher fit LF: Lower fit, MMSE: Mini Mental Status Examination, TICS-M: The Telephone Interview for Cognitive Status.

Memory performance declines with advancing age. Moreover, age-related memory losses are substantial in episodic memory tasks (Thielen et al., 2016). Thielen et al. (2016) showed that PA is positively associated with performance on an associative face-profession encoding task. The authors combined measures of systemic inflammation (interleukin 6, IL-6) and fMRI to investigate the effects of PA in healthy elderly. However, IL-6 does not represent the whole complexity going on in inflammatory processes. For the analysis, the participants were grouped based on two levels of self-report aerobic PA. The high PA group had better memory performance for face-profession associations compared to the low PA group. Moreover, the scores on tests assessing visual processing speed, working memory, and verbal fluency were higher in the high PA group (Thielen et al., 2016). Smith et al. (2011) examined the interactive effects of apolipoproteinE-ε4 (APOE-ε4) allele which is a genetic risk factor for Alzheimer's disease and PA on brain activation during memory processing. Participants were classified into four subgroups based on the PA level and presence of APOE-ε4 (Smith et al., 2011). The authors showed that enhanced semantic memory processing was observed in more physically active individuals, and this activation difference was most pronounced in those who possessed one or both APOE-ε4 alleles. Although the four subgroups have an equal sample size (n = 17) and matched on demographic variables it should be noted that the sample size is relatively small for group comparisons (Smith et al., 2011).

Zlatar et. al (2013) investigated whether PA mitigates age-related brain changes in the neural substrates of language function. Results indicate that brain function in the physically active older adults resembles that of younger adults, while the sedentary group showed reductions in negative task-related activity in areas of the attention network. Interestingly, even with a small sample size, group differences were found. Thus, it is possible that significant differences in semantic fluency would have emerged given a larger sample. In conclusion, PA may mitigate the effects of brain aging on language functions (Zlatar et al., 2013). The same authors performed a study using a fMRI motor task (McGregor et al., 2011). Patterns of cortical motor activity in older adults, who were either physically active or sedentary, were compared. Active older adults were closer to younger adults and evidenced longer ipsilateral silent periods and less positive blood oxygen level-dependent (BOLD) activation of ipsilateral motor cortex when compared to sedentary older adults. The findings suggest that increased PA seems to decrease aging-related losses of interhemispheric inhibition (McGregor et al., 2011).

Regarding studies that evaluate PA by accelerometry, Voss et al. (2016) and Kimura et al. (2013) indicate the validation criteria for the PA data (Kimura et al., 2013; Voss et al., 2016). Furthermore, in Kimura et al. (2013) PA was recorded for a higher period (3 months) compared to the usual period of 7 days in most studies. Specifically, the authors examined differences in brain activity patterns during an executive function task as a function of PA daily activity. Findings showed reduced age-related prefrontal activation in the higher PA group. Furthermore, the study identified PA parameters related to cognitive status indicating that the daily PA equivalent of brisk walking (< 3 METs) might be a beneficial factor influencing and maintaining neurocognitive function in healthy older individuals (Kimura et al., 2013).

Voss et al. (2016) evaluated the FC of resting-state networks and found a positive relationship with cardiorespiratory fitness. The strongest effect was observed in the Default Mode Network (DMN). However, the authors did not find any association between MV-PA or light physical activity and FC. Moreover, the results also indicated that the DMN, executive control network, and salience network are the most disrupted with advanced age (Voss et al., 2016).

Longitudinal studies

A total of 8 longitudinal studies examined the relationship between PA and brain structure. From those, 5 studies measured PA by self-reported questionnaires (Table 6) and 3 measured PA by accelerometry (Table 7).

Table 6. Summary of longitudinal studies reporting the effects of physical activity measured by self-reported questionnaires on brain structure.

Study	Participant groups	Sample size	Mean age ± SD	Number of females	Follow-up time	Cognitive screening test	PA assessment	Neuroimaging assessment	Findings
Podewils et al. (2007)	Cognitively stable	60	77.3 ± 5.8	37	5 years	3MSE TICS CES-D	MLTPAQ	WM lesions	Positive association between PA and WM lesions progression in the cognitive stable group. and DWM lesion progression.
	AD	59	77.2 ± 5.8	37					
	MCI	60	77.0 ± 5.4	37					

Erickson et al. (2010)	Quartiles based on blocks walked: Q1	91	72.9± 3.7	182	At 9-year and 13-year	3MSE TICS DSST IQCODE CES-D 10-item DQ	MLTPAQ (baseline assessment)	GM volume	Greater walking distances were associated with greater GM in the frontal, occipital and temporal regions including the entorhinal cortex and hippocampus 9 years later. Walking relatively long distances (72 blocks) was necessary to detect differences in GM 9
	Q2	57	72.7± 3.7						
	Q3	78	73.2 ± 3.6						
	Q4	73	72.45±3.61						

									years later.
Smith et al. (2014)	Subgroups base on PA level and presence of APOE-ε4: Low Risk/High PA	24	74.4 ± 5.2	15	18-month	MMSE DRS-2 GDS	SBAS	GM and WM volume	Hippocampal volume decreased by 3% in the High Risk/Low PA group. Similar PA effects were not observed in the thalamus, caudate, amygdala, caudal middle frontal gyrus, pre-central gyrus, total GM, or cortical WM volumes.
	Low Risk/Low PA	34	72.2 ± 4.6	27					
	High Risk/High PA	22	71.5 ± 4.2	17					
	High Risk	17	73.7 ± 5.5	10					

	Low PA								
Tian, et al. (2014)	Sedentary	39	73.1 ± 2.9	162	9 years	3MSE DSST CES-D	MLTPAQ	WM, GM and WMH volumes WM integrity	Lower MD in the medial temporal lobe and cingulate cortex in the exercise active group compared to the sedentary group. Associations between PA and other neuroimaging markers were not significant.
	Lifestyle active	148	72.9 ± 2.8						
	Exercise active	89	72.7 ± 2.6						

Young et al. (2016)	Supervets (super veteran athletes)	27	67.88 ± 5.45	6	12-month	MMSE GDS SRT DSST Trail Making Test A and B COWAT 20-Word Item Episodic Memory Task Backward Digit Span PRMQ	PASE	GM volume, cortical thickness and WM volume/integrity	Higher WM AD in supervets compared to controls at the follow-up time point. No differences in volume or cortical thickness.
	Controls (non-sedentary control)	23	68.35 ± 5.81	9					

						Prospective Memory Card Sort Task Focal and Non-Focal Prospective Memory Task RVIP Stroop-Switch Task			

3MSE: Modified Mini Mental State Examination, AD: Axial Diffusivity, APOE-ε 4: apolipoproteinE-ε 4, CES-D: Center for Epidemiologic Studies Depression Scale, COWAT: Controlled Oral Word Association Test, DQ: Dementia Questionnaire, DRS-2: Mattis Dementia Rating Scale 2, DSST: Digit Symbol Substitution Test, DWM: deep white matter, GDS: Geriatric Depression Scale, GM: grey matter, IQCODE: The Informant Questionnaire on Cognitive Decline in the Elderly, MCI: Mild Cognitive Impairment, MLTPAQ: Minnesota Leisure Time Physical Activity Questionnaire, MMSE: Mini Mental State Examination, PASE: Physical Activity Scale for the Elderly, PRMQ: Prospective and Retrospective Memory Questionnaire, RVIP: Rapid Visual Information Processing, SBAS: Stanford Brief Activity Survey, SRT: Simple Reaction Time, TICS: The Telephone Interview for Cognitive Status, WM: white matter, WMH: white matter hyperintensities.

Table 7. Summary of longitudinal studies reporting the effects of physical activity measured by accelerometry on brain structure.

Study	Participant groups	Sample size	Mean age ± SD	Number of females	Follow-up time	Cognitive screening test	PA assessment	Neuroimaging assessment	Findings
Yuki et al. (2012)	Brain atrophy nonprogression group	774	60.4 ± 7.3	393	8 years	WAIS-R MMSE CES-D	Lifecorder (7 days) (uniaxial accelerometry sensor)	GM atrophy	High level of PA and total energy expenditure suppressed the frontal lobe atrophy progression.
	Brain atrophy progression group								No significant differences between temporal lobe atrophy progression and PA

									or total energy expenditure.
Arnardottir et al. (2016)	GM low	176	80.3 ± 4.6	215	5-year	MMSE DSST GDS MINI	Self-report questionnaire (at baseline) ActiGraph GT3X (7 days) (at follow up)	GM and WM volume	More GM and WM at baseline was associated with more total PA. 5-year change in both GM and WM was associated with less total PA. Less WM at follow-up and the WM 5-year change was associated with
	GM high	176	77.9 ± 3.7						
	WM low	176	80.6 ± 4.5						
	WM high	176	77.6 ± 3.7						

									sedentary behavior.
Best, et al. (2017)	No groups	141	72.5 ± 2.5 (at baseline)	84	13 years	3MSE	MLTPAQ (annually) SenseWear Armband (at 13 year) (3 days)	GM and WM volume and integrity	Maintenance of time spent walking predicted less reduction in hippocampal volume, smaller increases in GM MD, and WM AD.

3MSE: Modified Mini Mental State Examination, AD: Axial Diffusivity, CES-D: Center for Epidemiologic Studies Depression Scale, DSST: Digit Symbol Substitution Test, GDS: Geriatric Depression Scale, GM: grey matter, MD: Mean Diffusivity, MINI: MINI International Neuropsychiatric Interview, MLTPAQ: Minnesota Leisure Time Physical Activity Questionnaire, MMSE: Mini Mental Status Examination, WAIS-R: WAIS-R: Wechsler Adult Intelligence Scale-Revised, WM: White matter.

Hippocampus

A longitudinal association between PA and hippocampus was reported in 4 studies. Smith et al. (2014) evaluated 18-month changes in hippocampal volume, in four participant groups classified as high or low PA and AD risk status which was defined by the presence or absence of the APOE-ε4 allele. The subgroups studied were low risk/high PA, low risk/low PA, high risk/high PA, and high risk/low PA. For baseline characterization, the authors assessed cognitive status through the MMSE and the Mattis Dementia Rating Scale 2 (DRS-2), and mood was assessed using the Geriatric Depression Scale (GDS). At baseline, the high-risk groups performed slightly worse on the MMSE compared to the low-risk groups, but within the normal range indicating intact cognitive abilities. Regarding the MRI results, hippocampal volume decreased by 3% in the high risk/low PA group and remained stable in the other groups. The protective effect of PA on hippocampal volume was observed only in APOE-ε4 carriers. The finding was specific for the hippocampus, since similar PA effects were not observed in the thalamus, caudate, amygdala, caudal middle frontal gyrus, pre-central gyrus, total GM, or cortical WM volumes. Lastly, the authors suggest that knowledge of the APOE genotype could be important to make recommendations to older adults regarding PA to maintain brain integrity, prevent future cognitive decline, and brain atrophy (Smith et al., 2014).

Best. et al. (2017) found that changes in time spent walking over one decade, independent of initial levels of walking, predicted less reduction in hippocampal volume, and alterations in global microstructural features, including increases in GM mean diffusivity (MD) and WM axial diffusivity (AD). The authors also examined the effects of walking on cognition, using the Modified Mini-Mental State Examination (3MS) at years 10 and 13, and whether walking-induced effects on brain structure correlated with changes in cognition. General cognition decreased slightly over time, with alterations in WM AD correlating with cognition. Findings suggest that long-term maintenance of regular walking in older age might benefit cognitive health through the preservation of WM integrity (Best et al., 2017). Additionally, the level of activity at initial stages, year 10 PA, and changes in PA over a shorter period (i.e., from year 6 to year 10), were not as predictive for the brain structure and cognition as the longer-term changes from year 1 to year 10. It is concluded that older adults should maintain regular walking throughout aging. The authors also recommended that clinicians should consider evaluating older adults regularly (e.g., annually or semi-annually) for their PA behavior and should track changes over time, to better understand an older adult's risk for cognitive and neural decline. An important strength of this study is the longitudinal assessment of PA, cognition, and brain structure, which allowed to show that earlier changes in PA predict later changes in cognition and brain structure (Best et al., 2017).

Erickson et al. (2010) examined the association between GM volumes, PA, and cognitive impairment. The diagnosis of cognitive impairment was performed through a neuropsychological battery that included 6 cognitive domains: premorbid intelligence, memory, language, visuoconstructional/visuospatial, executive functions, and motor functions (Table 6). Results demonstrated that walking greater distances were associated with both larger hippocampal and GM volume 9 years later. Moreover, PA reduced the risk for cognitive impairment 2-fold. Despite these results, this study only used a single assessment of brain volume, thus future research should examine brain morphology using multiple neuroimaging time points (K. I. Erickson et al., 2010).

Finally, Young et al. (2016) compared veteran athletes with non-sedentary control volunteers. However, they did not find differences either in hippocampal volume changes at baseline or over the 12-month follow-up (Young et al., 2016).

WM and GM brain volumes

Age-related brain atrophy occurs due to the volume loss in WM, GM, and WM lesions (Arnardottir et al., 2016). Arnardottir et al. (2016) showed increases in GM and WM volumes, and less 5-year atrophy in these volumes associated with more PA, and more 5-year atrophy in WM associated with more sedentary behavior. Findings suggest that the longitudinal relationship between brain volumes and PA could be bidirectional, i.e., brain atrophy causes less PA and vice versa. Despite these results, the authors have different measurements of the PA at baseline (self-report questionnaire) and at follow-up (objective measurement) and sedentary behavior was not measured at baseline. Therefore, the observed association could become attenuated (Arnardottir et al., 2016).

Erickson et al. (2010) investigated whether PA, assessed at baseline, predicted GM volume 9 years later. The results showed that walking greater distances were associated with greater GM in frontal, occipital, and temporal regions. The authors established a minimum amount of PA (i.e., walking relatively long distances: 72 blocks) necessary to protect against the loss of GM volume and the development of cognitive impairment (K. I. Erickson et al., 2010). Yuki et al. (2012)

showed that a high level of PA and total energy expenditure suppressed atrophy progression in the frontal lobe, but not in the temporal lobe, over 8 years. Moreover, low-activity energy expenditure and a low number of steps were risk factors for frontal lobe atrophy progression in males, but not in females. The authors suggest that 30 min of middle-intensity or greater activities per day (i.e., 5700 steps per day or more) may be necessary to reduce the risk of frontal lobe atrophy progression (Yuki et al., 2012).

Podewils et al. (2007) evaluated the association of PA with the progression of WM lesions in AD, MCI, and cognitively stable participants, over 5 years. The authors found no evidence that higher levels of PA decreased the rate of WML. Additionally, the analyses stratified by neurocognitive outcome (cognitively stable, MCI, AD) revealed a significant association between increasing levels of PA and both PV and deep white matter (DWM) lesion progression, restricted to individuals who remained cognitively stable over the follow-up. Nonetheless, potentially no differences in WML progression were detected due to the rate of progression being slower than anticipated. Moreover, participants who developed MCI and AD had higher baseline levels of WML and accelerated progression of WMLs which may have limited the ability to detect the effect of PA on WMLs (Podewils et al., 2007).

Brain microstructure

Three longitudinal studies using DTI were identified on the relationship between PA and brain microstructure. Tian et al. (2014) quantified the associations between PA and microstructural integrity of GM and WM, accounting for health-related conditions, over 9 years. The exercise active group had lower MD in the medial temporal lobe and cingulate cortex than the sedentary group. These results were attenuated after adjustment for diabetes. The authors suggest that being active, such as walking, exercising, or doing recreational activities at least 1000 kcal every week, may be ideal for microstructural integrity in GM (Tian et al., 2014). Best et al. (2017) indicated that maintenance of time spent walking over a decade predicted increases in GM MD and WM AD (Best et al., 2017). Finally, Young et al. (2016) observed higher WM AD in veteran athletes compared to non-sedentary control volunteers at the follow-up time point (Young et al., 2016).

Risk of bias in individual studies

Results from quality assessment for each study are presented in Supplementary Tables 1–3. Most of the studies (63 %) presented good quality for the evaluated parameters. Only 12 studies had fair quality.

5. Discussion

Worldwide, the older population is growing due to the global rise in life expectancy. However, one of the biggest challenges is decline in brain health/cognitive function that usually associates with aging, which can impact negatively on autonomy and quality of life. Therefore, strategies for healthy brain aging are an important research focus and societal need. On this, there is increasing evidence that PA contributes to brain health, including both at the levels of brain structure and function. In this systematic review, we identified and explored observational cross-sectional and longitudinal MRI studies that address the impact of PA on brain structure and function in healthy older adults.

Altogether, findings evidence that PA may attenuate the age-related decline in brain regions vulnerable to dementia, including the hippocampus, temporal, and frontal regions. Specifically, its benefits on the hippocampus is the most consistent finding independently of study design, with findings reporting a positive association between PA and hippocampal volume (that is, regular PA may attenuate the age-related decline in hippocampal volume). Hippocampal atrophy is associated with cognitive decline, memory impairment and dementia, and is a well-established neuroimaging biomarker in the preclinical stages of AD (Arenaza-Urquijo et al., 2017; Hashimoto et al., 2017; V. R. Varma et al., 2015). Hippocampal changes occur with aging with estimates of around 1% annual reduction for older individuals over 50 years of age (Best et al., 2017; Brown et al., 2014). However, different levels of PA (i.e., low-intensity walking activities, moderate- to vigorous-intensity activities, and sedentary behaviors) may have varying effects on hippocampal volume. It is also not clear what is the frequency, duration, and PA intensity, with most beneficial effects in the hippocampus.

Remarkably, the literature analysis suggests that the protective effects of PA appear to be greater in carriers of the APOE-ε4 allele compared to non-carriers, and in individuals who are BDNF Val/Val homozygotes compared with Met carriers. This is interesting because BDNF Val and

APOE-ε4 alleles confer susceptibility to AD, and the effects of PA seem to be greater in brain regions vulnerable to dementia. Therefore, more information is needed for the development and implementation of PA promotion strategies and recommendations to achieve better benefits, as well as on the nature of this association.

Structural MRI studies also demonstrate that PA is associated with larger GM volume and preserved GM in the prefrontal cortex, increased GM density and thickness in frontal regions, and appears to suppress frontal lobe atrophy progression. Furthermore, 30 min of middle- or greater intensity activities per day (i.e., 5700 steps per day or more) may be necessary to reduce the risk of frontal lobe atrophy progression. These findings are in agreement with a previous review from Erickson et al. (2014) indicating that PA effects are regionally specific to areas that tend to decline earlier in adulthood and that support executive and memory functions (i.e., the prefrontal cortex and hippocampus). This regional specificity may be related to their sensitivity to molecular changes resulting from PA (Kirk I. Erickson et al., 2014). Despite this, it is not possible to establish a concrete association given both the high heterogeneity in measurement methods used for PA assessment and the variability of the dimensions evaluated (frequency, intensity, duration, walking distances, energy expenditure, and exercise engagement).

Consistent with previous studies, results also evidence the beneficial effects of PA on the temporal lobe. Higher levels of PA associate with greater GM, increased GM density, better medial temporal lobe integrity, and less age-related atrophy in the temporal region. While some studies report the effect for high levels, others report for greater walking distances (72 blocks) or for individuals who meet recommended levels of PA. The literature has shown that temporal lobe atrophy occurs in normal aging and can predict cognitive decline to AD. Additionally, PA has been proposed to attenuate this age-related decline in the temporal lobe (Dougherty et al., 2016). Therefore, due to the high potential of PA to prevent or reduce the risk of cognitive decline and dementia it is important to elucidate on recommendations concerning frequency, duration, and intensity.

Additionally, a less consistent positive effect in the parietal region was here found. This region is known to be susceptible to age-related deterioration, or AD, and has an important role in several cognitive functions, including attention, language, visuospatial, and action-related (Lee et al., 2016). Furthermore, frontoparietal regions are highly vulnerable to changes in blood oxygenation levels, due to exercise-induced vascularization (Tian et al., 2014). Therefore, these regions may selectively benefit from the exposure to higher PA.

A few studies explored the efficacy of PA in mitigating WMH progression. While some authors report that leisure-time PA was not significantly associated with WMH, others found a greater MV-PA associated with lower WM lesions. WMH are commonly detected through MRI in the brain of elderly individuals. More than 90 % of the population over 80 years of age has some degree of WMH (Brugulat-Serrat et al., 2019). The pathogenesis of WMH reflects multiple pathologic changes, including loss and deformation of the myelin sheath, occlusion of small cerebral vessels, ischemic lesions, and damage to the blood-brain barrier (Brugulat-Serrat et al., 2019; Burzynska et al., 2014). WMH have been shown to exert a negative impact on multiple cognitive domains and to constitute an independent risk factor for cognitive decline and for the risk of developing AD. WMHs particularly affect executive function, processing speed, and memory (Brugulat-Serrat et al., 2019). Since WMH progression can be delayed by controlling vascular risk factors, MV-PA could slow the progression of WMH by increasing cardiovascular health.

Regarding studies that examined brain function, a positive relationship with PA is observed. Aging is associated with declines in performance on cognitive tasks, including memory, processing speed, and executive function (Harada, Natelson Love, & Triebel, 2013; Sala-Llonch, Bartres-Faz, & Junque, 2015). fMRI is a non-invasive approach to explore the association of age-related cognitive decline with patterns of altered brain activity (McDonald, D'Arcy, & Song, 2018; Sala-Llonch et al., 2015). This widely used technique is based on changes in BOLD signal to identify areas of increased or decreased neuronal activity during task performance or task-free resting-state (Fox & Greicius, 2010; McDonald et al., 2018). Here, most identified studies focused on the use of cognitive tasks to explore the role of PA in functional brain activation. Task-related fMRI studies evaluated the difference in BOLD signal between the task phase and the resting phase (baseline) providing a robust indicator of task-relevant neural recruitment (McDonald et al., 2018). Concerning the cognitive tasks used, a great variability in the cognitive domains tested (e.g., executive function, memory, language, and motor function) is noted. Thus, the small number of studies identified and the great variability across study protocols, limit the conclusions that can be drawn. However, results suggest that PA is a beneficial factor that may mitigate the effects of brain aging in cognitive function by preventing or delaying cognitive decline. Moreover, the protective effects appear to be greater in carriers of the APOE-ε4 allele compared to non-carriers. Thus, PA may protect against cognitive decline, especially among healthy older adults at genetic risk for dementia. Additionally, brain function in physically active older adults resembled younger adults compared to sedentary older adults. Typically, older adults show higher activity levels in some brain regions during the performance of cognitive tasks, which can be interpreted as a compensatory mechanism (Sala-Llonch et al., 2015). Lastly, fMRI studies with cognitive tasks suffer from intra and inter-subject variability, scanner variability, are dependent on task performance, and often involve lengthy scan times with complex study designs and are difficult to standardize (Fleisher et al., 2009).

On the other hand, resting-state fMRI (rs-fMRI) studies have the advantage to remove the confounding effect of differences in task performance (Fox & Greicius, 2010; Voss et al., 2016), and are suitable for studying patient populations who cannot perform tasks very accurately due to physical or cognitive impairment (Fox & Greicius, 2010). rs-fMRI FC studies in older adults allow to conclude that higher levels of activity coexist with disrupted connectivity (Sala-Llonch et al., 2015). The association between age and network integrity tends to be stronger in specific networks (McGregor et al., 2011). In this review, only one study using rs-fMRI was identified, with authors reporting a positive relationship between cardiorespiratory fitness and FC, but not with PA. The positive relationship is noted in the DMN, executive control network, and salience network, with the strongest effect in the DMN. The authors predict that the strongest associations with fitness or PA would occur in regions that are vulnerable to adverse effects of ageing, including the prefrontal and temporal cortices (Voss et al., 2016).

The neuroprotective effects of PA in the brain could be explained by several underlying mechanisms, including increased blood flow through vascularization (Lee et al., 2016; Tian et al., 2014; V. R. Varma et al., 2015), angiogenesis, activation of the immune system, and induction of neurotrophic factors (V. R. Varma et al., 2015). Research in animal models has provided mechanistic evidence of the influences on brain volume and function in humans, suggesting effects in the promotion of the proliferation and survival of new neurons in the hippocampus. Additionally, these new cells require increased nutrients, which are supplied by new vasculature (K. I. Erickson et al., 2010). The increase in cerebral blood flow seems to be associated with the neural activation, cholinergic enhancement and possibly reduces the amyloid burden (Smith et al., 2014). Animal studies also demonstrated that PA promotes an increase in cerebral neurotrophin levels, and subsequently has beneficial effects on neurogenesis, synaptic plasticity, and learning ability (Floel et al., 2010; Smith et al., 2014). Additionally, human studies have shown that PA increases peripheral levels of neurotrophins (Floel et al., 2010). For instance, it is associated with the induction of BDNF (Brown et al., 2014; Zlatar et al., 2015), which is critical for inducing neuroplasticity from neurogenesis to neuronal survival, from synaptogenesis to cognition (Miranda, Morici, Zanoni, & Bekinschtein, 2019), and reducing indices of neurodegeneration (Brown et al., 2014; Zlatar et al., 2015). Moreover, this effect appears to be genotype-dependent since BDNF secretion is more efficient in Val/Val homozygotes, compared with Met carriers (Brown et al., 2014; Zlatar et al., 2015). Thus, BDNF secretion may have a stronger effect on individuals at risk of AD by protecting against AD-related neurodegeneration. Additionally, PA appears to benefit APOE-ε 4 allele carriers more than APOE-ε 4 allele non-carriers Brown et al., 2014; Zlatar et al., 2015). APOE-ε 4 allele results in the disruption of lipid homeostasis, with adverse effects on amyloid precursor protein function, clearance of brain amyloid, neuroinflammation, and acetylcholine function. The lipoproteins resulting from the APOE-ε 4 allele are removed more easily in carriers, and this greatly reduces the amount of APOE available in the brain compared to non-carriers. This leads to reduced levels of brain free fatty acids that are essential for neuronal repair and neurotrophic processes (Smith et al., 2014).

Regarding the PA recommendations to promote and/or achieve better health, the American College of Sports Medicine (ACSM) and the American Heart Association propose 150 min of moderate-intensity PA or 75 min of vigorous-intensity, or an equivalent combination of moderate and vigorous PA per week; where, for older adults, the aerobic intensity is defined as moderate intensity at 5–6 on a 10-point scale and vigorous-intensity at 7–8 on a 10-point scale (Nelson et al., 2007). However, for instance, the effect of meeting PA recommendations on brain volume is unknown. Furthermore, some authors establish a minimum amount of PA (walking 72 blocks), others recommended a daily PA equivalent of brisk walking (< 3 METs), or 30 min of middle-intensity or greater activities per day (i.e., 5700 steps per day or more), or recreational activities of at least 1000 kcal every week. Based on the literature analyzed in this review, and even without consensus on PA recommendations, we suggest that older adults should be engaged in regular exercise for at least 30 min on a daily basis and reduce sedentary time. More so, altogether, it seems that the participation in low-intensity activities might benefit brain health; therefore, we recommend starting with these activities in case of people that have not been active and increase to more vigorous intensity adapted to an individual level (based on personal factors such as the level of frailty or current fitness status). Finally, we highlight the importance of long-term maintenance of regular physical activity (even low-intensity), as well as the potential need for the ACSM recommendation to be revised so to address the recommendation of Nelson et al. (2007) when considering older adults (Nelson et al., 2007).

Methodologic considerations

Studies examining the effects of PA on brain structure and function in healthy aging populations are very recent (starting in 2007), with the majority having a cross-sectional design. Thus, while valid conclusions regarding more complex associations of change, or causality, are not possible (Levin, 2006; Lindwall et al., 2012), they provide a useful snapshot of the effects of PA in brain health and could be used to generate new hypotheses and for planning public health interventions (Levin, 2006). On the other hand, longitudinal studies, even if observational, provide stronger evidence offering valuable information on the relationship between PA and brain health.

Here, a limitation was the scarcity of longitudinal studies. Besides this, some studies did not examine changes in the brain over time (i.e., only have a single MRI measure at baseline or follow-up). Furthermore, the non-uniformity in the collection of PA data is also of mention. Some of the studies use a single assessment of PA at baseline or follow-up, while others use different measurements of the PA at baseline and follow-up (e.g., measured PA at baseline by self-report questionnaires and at follow-up via an objective method). Finally, it should be noted that, as Best et al. (2017) indicate, PA is not stable over longer periods which means that individuals identified as highly active might not be consistently highly active over months or years (Best et al., 2017). Thus, it would be useful to perform longitudinal studies using objective measurements of PA, both at baseline and follow-up, with consistent measures of PA and brain structure and/or function over time. Additionally, 72 % of the studies evaluated PA with self-report questionnaires, with limited validity in capturing the full range of daily living activities and with limitations associated with an inaccurate recall. In contrast, wearable sensors can provide an objective and precise assessment of everyday activities and may allow the identification of a specific PA pattern across time (Kirk I. Erickson et al., 2014; Schwenk et al., 2015). These sensors incorporate measures of several activities including exercise, non-exercise, lifestyle activities (e.g., walking), and instrumental activities of daily life (e.g., housework). In general, these measures indicate the amount of total movement within an individual's environment (Vijay R. Varma et al., 2016). Moreover, this technology allows determining the PA intensity and duration without intervention from participants to self-report their activities (Kirk I. Erickson et al., 2014). That is, objective measures are extremely important to capture the low-intensity PA (particularly if considering that many older adults are sedentary). Despite these advantages, there are many issues regarding data reduction algorithms, processing criteria, such as non-wear time rules, that might have a profound influence on PA and sedentary time estimates, and in the associations with brain variables. In this review, it was observed that the criteria for valid PA data were different in the studies identified, ranging from 10 h as a valid wear-time, and a minimum of three valid days, to at least 10 h of valid time per day for a minimum of three weekdays and one weekend day. Thus, it is necessary to standardize these criteria to secure the highest data quality and consistency among studies.

Regarding the neuroimaging assessment, the outcomes reported were highly variable and the studies focused mainly on single brain biomarkers. Therefore, there is a need for future multimodal imaging studies and the standardization of MRI techniques for the acquisition and data analysis.

Finally, an additional limitation was the sample size. One-fourth of the included studies had a relatively small sample size (< 50 participants). This may affect the statistical power and limit the interpretation of the results and p-values. Another critical finding is that most studies had a higher percentage of female participants. Further, two studies reported only significant results for women (V. R. Varma et al., 2015; Vijay R. Varma et al., 2016). This may indicate that there is a sex difference in biological responses to PA, which could be explained by sex hormones that may affect the relationship between PA and brain health. Therefore, it is important to clarify this sex-specific association of PA with brain health, via balanced cohorts regarding sex-distribution and/or representative of the population.

Limitations

Despite the exhaustive search strategy across several databases, the search relied on a limited number of databases with restriction of studies published in the English language. Therefore, it is possible that potentially eligible studies were omitted. Moreover, grey literature and reference lists of included studies were not searched. The search methodology was not reproduced by an independent reviewer; however, a double screening was performed, and a strict procedure was followed accordingly to PRISMA guidelines. Publication bias must be considered because studies with statistically significant results are more likely to get published over studies without significant results. Finally, substantial heterogeneity was observed among the included studies and our review did not consider confounding factors.

6. Conclusions

Future research should explore which parameters, including intensity, frequency, or duration, have more beneficial effects on the brain regions that are sensitive to PA. Moreover, due to the numerous methodological issues that limit the comparisons across studies, higher research methodology standards are needed including standardization measures of: (i) study protocols; (ii) MRI techniques for the acquisition and data analysis; (iii) objective assessment of PA with a clear definition for data validation and cut off values for the definition of PA intensities; (iv) neuropsychological batteries assessing multiple domains of cognition. Whenever possible studies should include larger sample sizes to have enough statistical power to detect significant effects of PA and as much as possible be representative of the population or contexts (and thus findings expandable). It is also important to explore the association between neuropsychological performance, brain structure and function, and the effect of multiple potential confounding variables as well as to address "practical and larger questions" in the field. For instance, as clear throughout this and other related reviews, it appears to be rather consensual that PA/ exercise provides benefits to brain functions. However, there is much scarcer evidence on how to design and implement context-based, adequate and efficacious programs, and motivate individuals to adhere to physical activities. A challenge for the scientific and healthcare community is thus to translate knowledge into best practices and communication with the population.

Despite the great variability across studies limiting the number of conclusions that can be drawn with certainty, this review provides additional evidence for the protective effects of PA in brain regions sensitive to neurodegeneration, including the hippocampus, temporal, and frontal regions. A better understanding of these region-specific associations with specific types of PA will enable clinical trials to better select target regions and/or types of PA interventions.

7. CRediT authorship contribution statement

C. Domingos: Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. J.M. Pêgo: Funding acquisition, Supervision, Validation, Writing - review & editing. N.C. Santos: Funding acquisition, Supervision, Validation, Writing - review & editing.

8. Declaration of Competing Interest

The authors declare that there is no conflict of interest associated with this publication.

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11. Supplementary material

Supplementary Table 1. Critical appraisal for cross-sectional studies evaluating brain structure.

Studies	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Score
Lee et al. (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Bugg et al. (2011)	Unclear	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Fair
Kim et al. (2016)	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Fair
Hashimoto et al. (2017)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Torres et al. (2019)	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Good
Boyle at al. (2015)	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Zlatar et al. (2015)	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Good
Ho et al. (2011)	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good

Arenaza et al. (2017)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Kharabian (2018)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Lamont et al. (2014)	Unclear	Yes	No	Yes	Yes	Yes	Yes	Yes	Fair
Brown et al. (2014)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Smith et al. (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Floel et al. (2010)	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Good
Burzynska et al. (2014)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Dougherty et al. (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Varma et al. (2015)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Varma et al. (2016)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good

Supplementary Table 2. Critical appraisal for cross-sectional studies evaluating brain function.

Studies	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Score
Thielen et al., 2016	Unclear	No	Yes	Yes	Yes	Yes	Yes	Yes	Fair
Zlatar et al., 2013	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Fair
McGregor et al., 2011	Yes	No	Yes	Yes	Yes	Unclear	Yes	Yes	Fair
Smith et al., 2011	Yes	Unclear	Yes	Yes	Yes	Unclear	Yes	Yes	Fair
Voss et al., 2016	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Good
Kimura et al., 2013	Unclear	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Fair

Supplementary Table 3. Critical appraisal for longitudinal studies evaluating brain structure.

Studies	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Score
Erickson et al. (2010)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Podewils et al. (2007)	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Good
Tian, et al. (2014)	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Good
Smith et al. (2014)	Yes	No	Yes	Unclear	Yes	No	Yes	Yes	Fair
Young et al. (2016)	Unclear	No	Yes	Yes	Yes	Yes	Yes	Unclear	Fair
Arnardottir et al. (2016)	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Fair
Yuki et al. (2012	Yes	Yes	Unclear	Unclear	Yes	Yes	Yes	Yes	Fair
Best, et al. (2017)	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Good

CHAPTER V

Association between free-living physical activity measured with a wearable device and healthy brain aging: an observational, cross-sectional study in Northern Portugal

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Association between free-living physical activity measured with a wearable device and healthy brain aging: an observational, cross-sectional study in Northern Portugal

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1. Abstract

Several studies using neuroimaging techniques have established a positive relationship between physical activity (PA) and brain structure and function in older populations. However, the use of subjective measures of PA and the lack of multimodal neuroimaging approaches have limited the understanding of this association. This study aims to explore the associations between PA and brain structure and function by objectively evaluating PA.

Community-dwelling cognitively healthy older adults (without diagnosed cognitive, neurological, or degenerative disease) were recruited from local health centers and local gyms. In a cross-sectional design, participants were evaluated regarding cognitive, clinical, anthropometric, physical performance, and lifestyle characteristics. A 3 T magnetic resonance imaging (MRI) was performed for structural and functional brain measures. PA time and level were assessed via a Xiaomi Mi Band 2® worn for 15 consecutive days.

Participants (n=110, after inclusion/exclusion criteria and completion of all evaluations) were 58 females (56%), with an average age of 68.42 years old (SD = 3.12), most were active. Multiple regression analysis revealed that higher time spent in vigorous PA associated with larger left parahippocampal gyrus and right hippocampus volumes. Furthermore, the analysis of the functional connectome indicated a greater FC between the frontal gyrus, cingulate gyrus, occipital inferior lobe for light, moderate, and total PA time, and sedentary time associated with lower FC in the same networks.

Overall, the structural and functional findings may provide evidence on the relevant association between PA and brain health in aging.

Keywords: Physical activity, elderly, brain health, neuroimaging, accelerometry.

2. Introduction

Due to the global rise in life expectancy, the older population is increasing worldwide (Boraxbekk, Salami, Wåhlin, & Nyberg, 2016; Prakash, Patterson, Janssen, Abduljalil, & Boster, 2011). This has led to a pressing need to understand patterns of both healthy and unhealthy aging processes. Normal aging is associated with changes in brain structure and function, with progressive brain atrophy, and age-related cognitive decline (Ho et al., 2011; Lee et al., 2016; Marques, Soares, Magalhães, Santos, & Sousa, 2016; Soares, Marques, Magalhães, Santos, & Sousa, 2014; Zlatar et al., 2015; Zlatar et al., 2013). In particular, the reductions in brain volume are most pronounced in prefrontal, temporal, and parietal gray matter (Zlatar et al., 2015). Furthermore, aging is the most important risk factor for the development of dementia (Kim et al., 2016), which in turn is one of the most pressing health issues due to the enormous costs from morbidity, mortality, and loss of independence (van der Flier & Scheltens, 2005; Voss et al., 2016; Wattmo, Londos, & Minthon, 2014). Therefore, healthy brain aging is an essential component of overall well-being (Joo, Lim, & Lee, 2016), with current public health goals encompassing the identification of mechanisms that contribute to brain health, protecting from structural and functional declines (Boraxbekk et al., 2016; Floel et al., 2010; Prakash et al., 2011).

Emerging evidence over the past decade has suggested the beneficial effects of physical activity (PA) on brain health and function, particularly in aging individuals (Bugg & Head, 2011; Floel et al., 2010; Zlatar et al., 2015). Research indicates that PA confers reduced risk for mild cognitive impairment and dementia and has beneficial effects in maintaining cognitive function in older adults (Siddarth et al., 2018; Voss et al., 2016). Additionally, multiple neuroimaging studies have shown that PA is predictive of larger hippocampal volume in healthy elderly individuals (Arenaza-Urquijo et al., 2017; Kleemeyer et al., 2016; Prakash et al., 2011). Additionally, it contributes to greater connectivity between the hippocampus and the anterior cingulate cortex (Boraxbekk et al., 2016) and positively correlates with higher gray matter volume in the prefrontal cortex in older adults (Kirk I. Erickson, Leckie, & Weinstein, 2014; Sexton et al., 2016; Yamamoto et al., 2017). PA has also been associated with superior white matter (WM) integrity using diffusion tensor imaging in descriptive and interventional studies (Tian et al., 2015), and with greater WM volume, reduced severity of WM lesions, and improvements in WM microstructure (Sexton et al., 2016; Tian et al., 2015). The brain network connectivity also appears to be highly influenced by PA (Prakash et al., 2011). Voss et al. (2016) mentioned that cardiorespiratory fitness has a positive relationship with the functional connectivity (FC) of several cortical networks associated with age-related decline, with the strongest effect in the default mode network (DMN) (Voss et al., 2016). Also, Boraxbekk et al. (2016) observed higher PA associated with stronger connectivity in the posterior DMN (Boraxbekk et al., 2016). Recently, Domingos et al. (2020) systematically review the relationship between PA and brain structure and function in older adults. This study provided compelling evidence that PA is associated with larger brain volumes (less brain atrophy), specifically in brain regions vulnerable to dementia, including the hippocampus, temporal, and frontal regions, and greater task-relevant activity in brain areas recruited in executive function and memory tasks (C. Domingos, Pêgo, & Santos, 2021).

In context, PA is a promising non-pharmacological interventional approach for promoting the health of the aging brain (Benedict et al., 2013; Bittner, Jockwitz, & Muhleisen, 2019; Sexton et al., 2016) since it is a cost-effective, safe and accessible intervention, and can reduce the need for (costly) drug treatments with negative side effects (Voss et al., 2016). Despite the evidence for associations between PA and brain health, this relationship is not fully established due to study limitations (Oberlin et al., 2016; Sexton et al., 2016; Tian et al., 2015). Most studies have relatively small sample sizes, are mainly based on single brain biomarkers, and/or employ subjective measures of PA (Boraxbekk et al., 2016; Oberlin et al., 2016; Yamamoto et al., 2017). Indeed, self-report questionnaires have been used to measure PA, with limited validity in measuring activities of daily living, including the limitations associated with a self-report activity. In contrast, wearable sensors can provide an objective and precise assessment of everyday activities and may allow the identification of specific PA patterns (Kirk I. Erickson et al., 2014; Schwenk et al., 2015) across time and populations. These sensors include tools to determine the PA intensity and duration without the need of intervention from participants to self-report their activities (Kirk I. Erickson et al., 2014). Furthermore, wearable systems are being increasingly cited as having great potential to improve the PA levels in the population, including older adults. However, more research must be done to fully understand the potential of this wearable technology as health interventions promoting behavioral changes (Mercer & Li, 2016).

The current study goes beyond previous works, by combining a multimodal imaging approach with an objective measurement of daily PA to explore brain health in an aging cohort and addressing some of the previous limitations. Specifically, in a cohort of cognitively healthy older adults, the study aim is to explore the association between PA dimensions and brain volume and function.

3. Methods

Participants

A convenience sample of 120 community-dwelling older adults was recruited from local healthcare centers and local gyms in the municipality of Braga in Northern Portugal. The eligibility criteria were: (1) age comprised between 65-75 years of age; (2) capacity to understand the informed consent; (3) ability to attend the MRI session (e.g., without metallic implants, pacemakers, claustrophobia); (4) ability to wear Xiaomi Mi Band 2® for fifteen consecutive days; (5) free of diagnosed neuropsychiatric, or neurodegenerative disorders; (6) adequate visual, auditory, and fine motor skills; and (7) not having any incapacity that limited independent walking. From the initial population, a final sample of 110 participants met all inclusion criteria and completed the study assessment sessions.

Data collection and instruments

The participant's characterization was performed through: (1) a structured questionnaire-based interview to assess socio-demographic, clinical, and lifestyle information; (2) a neuropsychological and quality of life evaluation; (3) an anthropometric and body composition evaluation; and (4) physical performance evaluation. Detailed information regarding the study evaluation moments is present in Figure 1. Based on the assessment type, measures were assessed always by the same attributed team member/researcher, following a study manual and/or established practices. Participants were instructed not to change their habitual daily living habits/routines.

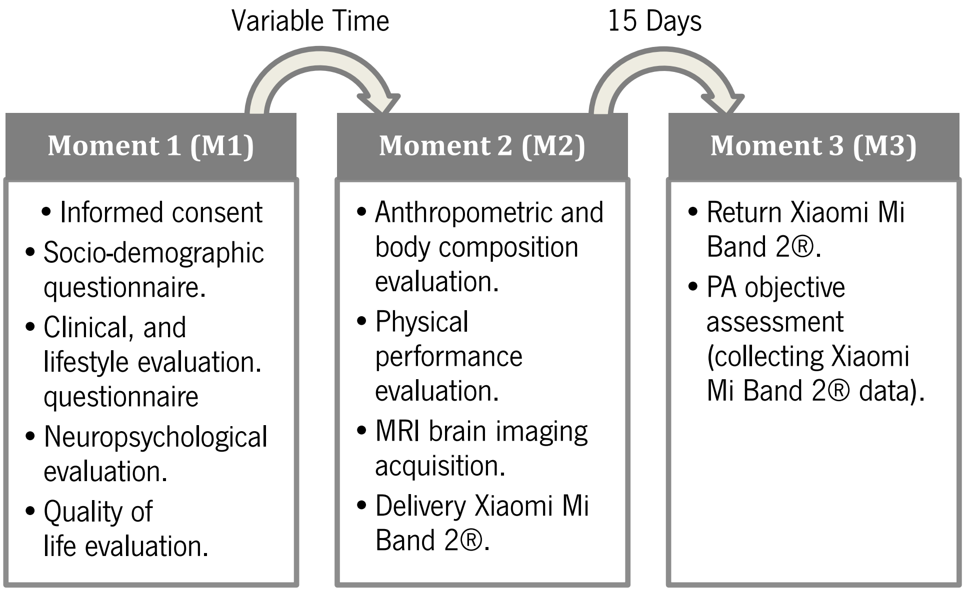

Figure 1. Flow diagram of the evaluation moments.

Clinical and lifestyle characteristics

Clinical measures included current medication, clinical history of stroke, cardiac pathology, diabetes (diabetes mellitus type I or II), dyslipidemia, hypertension, psychiatric disorders, neurological disorders, chronic kidney disease, cancer, musculoskeletal disorders, digestive diseases, and chronic obstructive pulmonary disease. The variables were categorized as absence or presence of chronic diseases. Polypharmacy was defined as the use of three or more medications daily (Masnoon, Shakib, Kalisch-Ellett, & Caughey, 2017). The measurement of right brachial blood pressure (BP) was performed with the subject in a seated position after 5 min of resting time. Three readings, at 2-min intervals, were taken, and the mean was used for analysis.

For lifestyle measures, alcohol consumption and smoking habits (non-smoker, former smoker, and smoker) were considered. Heavy smokers were classified as smoking 25 or more cigarettes a day (Wilson, Wakefield, Owen, & Roberts, 1992) and excess alcohol consumption was considered more than 4 drinks per day for men and more than 3 drinks a day for women (National Institute of Alcohol Abuse and Alcoholism).

Comorbidity Index was calculated using the number of chronic conditions, polypharmacy, and lifestyle-related risk factors such as drink and smoking habits.

Anthropometric characterization

The anthropometric evaluation included weight (Tanita BF 350 Body Composition Analyzer), height (Seca 217 Stadiometer), waist (WC), and hip circumferences (HP) (Ergonomic Measuring Tape). Body mass index (BMI) was obtained as weight (kg)/height (m2) and classified as underweight, normal, overweight, and obese (respectively, BMI: [0–18.5], [18.6–24.9], [25.0–29.9], and [30.0+]) (Organization, 2011). The waist-to-hip ratio (WHR) was calculated by dividing the WC (cm) by HP (cm) circumference (Organization). WHR above 0.90 for males and above 0.85 for females was classified as a substantially increased risk of metabolic complications (Organization, 2011).

Body composition

Body composition was assessed by bioelectrical impedance using a Maltron BioScan 920-II Multi-frequency Analyzer. The analysis was performed according to manufacturer instructions. The optimal cut-off values for body fat (FAT) percentage were defined as ≤ 42% for women and ≤ 30% for men (Pérez-Ros, Vila-Candel, López-Hernández, & Martínez-Arnau, 2020).

Physical performance

The assessment of physical performance included gait speed (6-meter walking test) and handgrip strength (Jamar Hand Dynamometer). In older individuals, the cut-off point for slow gait speed was defined as walking less than 1 m/s, which identifies persons at high risk of health-related outcomes in well-functioning (Cesari et al., 2005). The normative data for handgrip strength ranges from 22.5 to 25.6 kg for women and 36.2 to 41.7 kg for men (Bohannon, Peolsson, Massy-Westropp, Desrosiers, & Bear-Lehman, 2006).

Functional status was evaluated using the Lawton Instrumental Activities of Daily Living (IADL) Scale to assess independent living skills (Lawton & Brody, 1969), Katz Activities of Daily Living (ADL) Scale to assesses six primary and psychosocial functions (bathing, dressing, going to the toilet, transferring, feeding, and continence) (Katz, Ford, Moskowitz, Jackson, & Jaffe, 1963), and Tinetti-test to assess the gait and balance (Tinetti, 1986).

Neuropsychological evaluation

A trained psychologist applied and scored all neuropsychological tests aiming to assess memory, executive function, general cognition, and mood. The Mini-Mental State Examination (MMSE) was used to assess the global cognitive profile (Guerreiro et al., 1994). The following cut-off scores for "cognitive impairment" were used: individuals with no education, <15 points; 1 to 11 years of school completed, <22 points; and >11 years of school completed, <27 points (Santana et al., 2016). The Selective Reminding Test (SRT) was used for verbal learning and memory (Buschke, Sliwinski, Kuslansky, & Lipton, 1995). The Digits Span Test (DSST) was used to test working memory and attention (Ryan & Lopez, 2001). The Stroop test assessed selective attention, cognitive flexibility, and response inhibition (Spreen & Strauss, 1998). To evaluate the level of interference when the name of a color is written in a different color ink the Golden index was used, with higher score means indicating decreased Stroop interference (Lansbergen, Kenemans, & van Engeland, 2007). Verbal fluency was evaluated through the Controlled Oral Word Association F-A-S (FAS) test (Lezak, Howieson, Loring, & Fischer, 2004). Finally, the Geriatric Depression Scale (GDS) was used to characterize depressive mood (Yesavage et al., 1982). GDS scores range from 0 to 30, representing the total number of depressive symptoms, with values >11 indicating the presence of depressive symptomatology (Pocinho, Farate, Dias, Lee, & Yesavage, 2009).

Quality of life assessment

Health-related quality of life was assessed using version 2.0 of the Portuguese 36-Item Short-Form Health Survey (SF-36) (Ferreira & Santana, 2003). The SF-36 is probably the most widely used generic health status measure used in clinical research, health policy evaluations, and general population surveys (Fryback et al., 2007; J. E. Ware, Jr. & Sherbourne, 1992). The survey consists of 36 items that assess eight health concepts: physical functioning (PF), role physical (RP), bodily pain (BP), general health (GH), vitality (VT), social functioning (SF), role emotional (RE), and mental health (MH). These domains may be reduced into the physical component summary (PCS) and the mental component summary (MCS). Items are scored by a Likert scale. All items of SF-36 are used to score the eight domains, except for item 2, which refers to a self-report of health transition. Each item contributes to only one domain. The scores range from 0 (worst health) to 100 (best health) (J. E. Ware & Institute, 1994; J. E. Ware, Jr., 2000).

Xiaomi Mi Band 2®

The wearable activity tracker selection was based on a review of the characteristics of several different commercially available devices on the market (El-Amrawy & Nounou, 2015; Liang et al., 2018; Xie et al., 2018). The selection criteria included the popularity in the wearable healthcare devices market, availability, continuous monitoring of PA without a smartphone, price, battery life, various sensors data captured, and ability to export data (Célia Domingos, Correia Santos, & Pêgo, 2021). The Xiaomi Mi Band 2® was selected because it offers the best price-quality ratio, has an estimated battery life of almost 30 days, is ergonomic, accessible, and easy to operate. The device measures steps, intensity, energy expenditure, and distance traveled (El-Amrawy & Nounou, 2015; Mičková, Machová, Daďová, & Svobodová, 2019; Puri et al., 2017; Xie et al., 2018). Additionally, Xiaomi Mi Band 2® demonstrated its high measurement accuracy (96.56%) and the relatively low variation coefficient (CV=5.81) (Xie et al., 2018).

Participants wore a Xiaomi Mi Band 2® for 15 consecutive days while performing their normal daily activities. The data was exported in SQLite format using a Master for Mi Band app and then converted in CSV format.

Data reduction

Microsoft Excel was used to perform data reduction and cleaning. Seven consecutive valid days of data were collected from the total wear time. For the analysis, we excluded the first day of records to ensure a complete day in each data collection period. Regarding data validation, each participant must have a minimum of 5 valid days, including at least one weekend day (Nicaise, Crespo, & Marshall, 2014; O'Neill et al., 2017), wherein a valid day consisted of at least 10 hours of records. An invalid hour was defined as more than 30 consecutive minutes with zero activity (Ferrari et al., 2020; Troiano et al., 2008). The PA intensities were defined using the following intensity-specific cut-points: sedentary 0–19 steps/min; light intensity:60–99 steps/min; moderate intensity: 100–119 steps/min; and vigorous-intensity: ≥120 steps/min (C. Tudor-Locke et al., 2011; Catrine Tudor-Locke et al., 2018).

MRI brain imaging acquisition

Sessions of MRI scanning were performed using a Siemens Verio 3T (Siemens, Erlangen, Germany) at Hospital de Braga (Braga, Portugal), using a 32-channel head antenna for reception. The scanning protocol included an anatomical acquisition with a T1-weighted (T1w) sagittal Magnetization-Prepared rapid acquisition with gradient echo (MPRAGE, TE/TR=2420/4.12 ms, FA=9°, 1 mm3 isometric voxel size, Field-of-View=176x256x256 mm3). For the resting-state functional magnetic resonance imaging (rs-fMRI) acquisition a multi-band Echo Planar Imaging sequence was used, CMRR EPI 2D (R2016A, Center for Magnetic Resonance Research, University of Minnesota, Minnesota, USA) (Feinberg et al., 2010; Moeller et al., 2010; Xu et al., 2013) sensitive to fluctuations in the BOLD contrast (TR/TE=1000/27 ms, FA=62°, 2 mm3 isometric voxel size, 64 axial slices over an in the plane matrix of 100 x 100). The rs-fMRI acquisition had a duration of seven and a half minutes, during which subjects were asked to remain relaxed and with their eyes closed.

Preprocessing of MRI data

Preprocessing was performed using fMRIPrep 1.4.1 proposed by Esteban et al. (2019); (RRID:SCR_016216) (Esteban et al., 2019), which is based on Nipype 1.2.0 (RRID:SCR_002502) (Gorgolewski et al., 2011).

Anatomical data preprocessing

T1w image was corrected for intensity non-uniformity (INU) with N4BiasFieldCorrection (Tustison et al., 2010), distributed with ANTs 2.2.0 RRID:SCR_004757(Avants, Epstein, Grossman, & Gee, 2008), and used as T1w-reference throughout the workflow. The T1w-reference was then skull-stripped with a Nipype implementation of the antsBrainExtraction.sh workflow (from ANTs), with OASIS30ANTs as target template. Brain tissue segmentation of cerebrospinal fluid (CSF), white matter (WM) and gray-matter (GM) was performed on the brain-extracted T1w using fast (FSL 5.0.9, RRID:SCR_002823) (Zhang, Brady, & Smith, 2001). Brain surfaces were reconstructed using recon-all (FreeSurfer 6.0.1, RRID:SCR_001847) (Dale, Fischl, & Sereno, 1999), and the brain mask estimated previously was refined with a custom variation of the method to reconcile ANTs-derived and FreeSurfer-derived segmentations of the cortical gray-matter of Mindboggle (RRID:SCR_002438) (Klein et al., 2017). Volume-based spatial normalization to standard space (ICBM 152 Nonlinear Asymmetrical template version 2009c (RRID:SCR_008796; TemplateFlow ID: MNI152NLin2009cAsym) (Fonov, Evans, McKinstry, Almli, & Collins, 2009) was performed through nonlinear registration with antsRegistration (ANTs 2.2.0), using brain-extracted versions of both T1w reference and the T1w template.

Resting-state data preprocessing

For each subject, the following preprocessing steps were performed: First, a reference volume and its skull-stripped version were generated using a custom methodology of fMRIPrep. A deformation field to correct for susceptibility distortions was estimated based on a field map that was co-registered to the BOLD reference, using a custom workflow of fMRIPrep derived from D. Greve's epidewarp.fsl script and further improvements of HCP Pipelines (Glasser et al., 2013). Based on the estimated susceptibility distortion, an unwarped BOLD reference was calculated for a more accurate co-registration with the anatomical reference. The BOLD reference was then co-registered to the T1w reference using bbregister (FreeSurfer) which implements boundary-based registration (Greve & Fischl, 2009). Co-registration was configured with nine degrees of freedom to account for distortions remaining in the BOLD reference. Head-motion parameters with respect to the BOLD reference (transformation matrices, and six corresponding rotation and translation parameters) were estimated before any spatiotemporal filtering using mcflirt (FSL 5.0.9) (Jenkinson, Bannister, Brady, & Smith, 2002). BOLD runs were slice-time corrected using 3dTshift from AFNI 20160207 (RRID:SCR_005927) (Cox, 1996). The BOLD time-series (slice-time corrected) were resampled onto their original, native space by applying a single, composite transform to correct for head-motion and susceptibility distortions, and finally resampled into MNI152NLin2009cAsym space. Several confounding time-series were calculated based on the preprocessed BOLD: framewise displacement (FD), DVARS [(derivative of root mean square variance over voxels) rate of change of BOLD signal across the entire brain at each frame of data], and three region-wise global signals. FD and DVARS are calculated for each functional run, both using their implementations in Nipype (following the definitions by Power et al. (2014) (Power et al., 2014). The three global signals were extracted within the CSF, the WM, and the whole-brain masks. Additionally, a set of physiological regressors were extracted to allow for component-based noise correction (CompCor) (Behzadi, Restom, Liau, & Liu, 2007). Principal components were estimated after high-pass filtering the preprocessed BOLD time-series (using a discrete cosine filter with 128s cut-off) for the anatomical variant (aCompCor). A mask covering the subcortical regions was obtained by heavily eroding the brain mask, which ensures it does not include cortical GM regions. For aCompCor, components were calculated within the intersection of the aforementioned mask and the union of CSF and WM masks calculated in T1w space, after their projection to the native space of each functional run (using the inverse BOLD-to-T1w transformation). Components were calculated separately within the WM and CSF masks. For each CompCor decomposition, the k components with the largest singular values were retained, such that the retained components' time series were sufficient to explain 50 percent of variance across the nuisance mask (CSF, WM, combined, or temporal). The remaining components were dropped from consideration. The mean CSF and WM signals, as well as the first 6 aCompCor components, the FD and the DVARS were regressed as confounds from the BOLD data using fslregfilt. Excessive movement was considered with a mean FD>0.25. Thus, subjects that exceeded this threshold were excluded. Finally, fslmaths was used to spatially smooth (with a FWHM kernel of 6mm) and band-pass filter (between 0.01 and 0.08 Hz) the resulting time-series.

Voxel-based morphometry (VBM)

FSL-VBM was used to analyze structural data (Douaud et al., 2007) an optimized VBM protocol (Good et al., 2001) conducted with FSL (S. M. Smith et al., 2004). First, structural images (which were already brain-extracted and grey matter-segmented by FMRIPrep) were registered to the MNI 152 standard space using non-linear registration (Andersson, Jenkinson, & Smith, 2007). The images obtained were averaged and flipped along the x-axis to create a left-right symmetric, study-specific GM template. Second, all native GM images were non-linearly registered to this study-specific template and "modulated" to correct for local expansion (or contraction) due to the non-linear component of the spatial transformation. The modulated GMimages were subsequently smoothed with an isotropic Gaussian kernel with a sigma of 3 mm.

Network Based Statistics (NBS)

Analysis of the functional connectome and correlation with variables of interest was carried using Network Based Statistics (NBS) (Zalesky, Fornito, & Bullmore, 2010). Time-series were extracted for each subject using a hybrid atlas using f the Shen atlas (Shen, Tokoglu, Papademetris, & Constable, 2013), with a total of 264 ROIs covering the entire brain. Matrices of FC were calculated through the fisher-z normalized Pearson correlation of each pair of time-series, producing a 264-by-264 matrix of FC per-subject. Associations between the variables of interest and networks of FC were calculated using the NBS methodology. NBS produces non-parametric FWE corrected results in two steps: first by calculating the hypothesis at each point in the matrix and detecting connected networks of results significant according to a user specified primary threshold; and second by calculating the significance of that network through permutation testing and comparing the extent of the network at a FWE-corrected p value of 0.05. Because different primary thresholds can yield networks of different nature it is recommended to explore a range of values. In this work, we tested N significance values between 0.005 and 0.00001. Visualization of the significant results was produced using BrainNet Viewer (Xia, Wang, & He, 2013). The scripts used to perform the analysis and produce all statistics are freely available online (https://osf.io/qepc8).

Statistical analysis

The sample size was calculated using GPower with an effect size of 0.32 (Gajewski & Falkenstein, 2016; Hogan, Mata, & Carstensen, 2013; Lautenschlager, Cox, & Cyarto, 2012). Descriptive analysis was performed for all variables. Quantitative variables were expressed as mean and standard deviation (SD), and the results for the categorical variables were expressed as percentages and 95 % confidence intervals. Normal data distribution was examined using the Shapiro–Wilk test, skewness, kurtosis, and histograms. Absolute values for skewness above 2.0 and kurtosis above 4.0 were considered as reference values for determining normality. A p-value below 0.05 for Shapiro–Wilk test indicates that the data significantly deviate from a normal distribution (Mishra et al., 2019).

To explore whether components of PA, including total PA, light, moderate, vigorous, and sedentary time, as measured cross-sectionally via the Xiaomi Mi Band 2® for fifteen consecutive days, associated with brain volume and resting-state networks (NBS), all PA components were analyzed separately, after controlling for age, gender, MMSE, and GDS. Positive and negative correlations were tested for all variables. Regarding VBM analysis, threshold-free cluster enhancement (TFCE) was used to detect widespread significant differences and control the family-wise error rate (FWE-R) at α = 0.05. Five thousand permutations were performed for each contrast. Moreover, the analysis was performed at the whole-brain level (using a grey matter mask), as well as using a hippocampus mask, due to the putative role of PA on this region (Arenaza-Urquijo et al., 2017; Kleemeyer et al., 2016; Prakash et al., 2011).

4. Results

Study Participants

The number and flow of participants from screening through enrollment are displayed in Figure 2 and the general participant's characteristics are summarized in Table 1. The older adults included in the final analysis had a mean age of 68.42 (SD ± 3.12), 56% were female, and the number of formal years of education was 7.75 (SD ± 5.28). Regarding the lifestyle habits, 9.6 % (n=10) were classified as heavy smokers, and 6.7 % (n=7) were considered as having an excess of alcohol consumption. In this sample, 23.1 % (n=24) were identified as having polypharmacy and 16.3 % (n=17) have a comorbidity index ≥ 5. The average BMI (28.83 ± 4.24) and the WHR ratio (0.95 ± 0.07) indicated that the older adults comprising the sample had a substantially increased risk of metabolic complications. The gait speed and handgrip strength were in the range of reference values, showing a good physical performance, and the functional status evaluation confirmed the independence in activities of daily living and performance of instrumental activities of daily living.

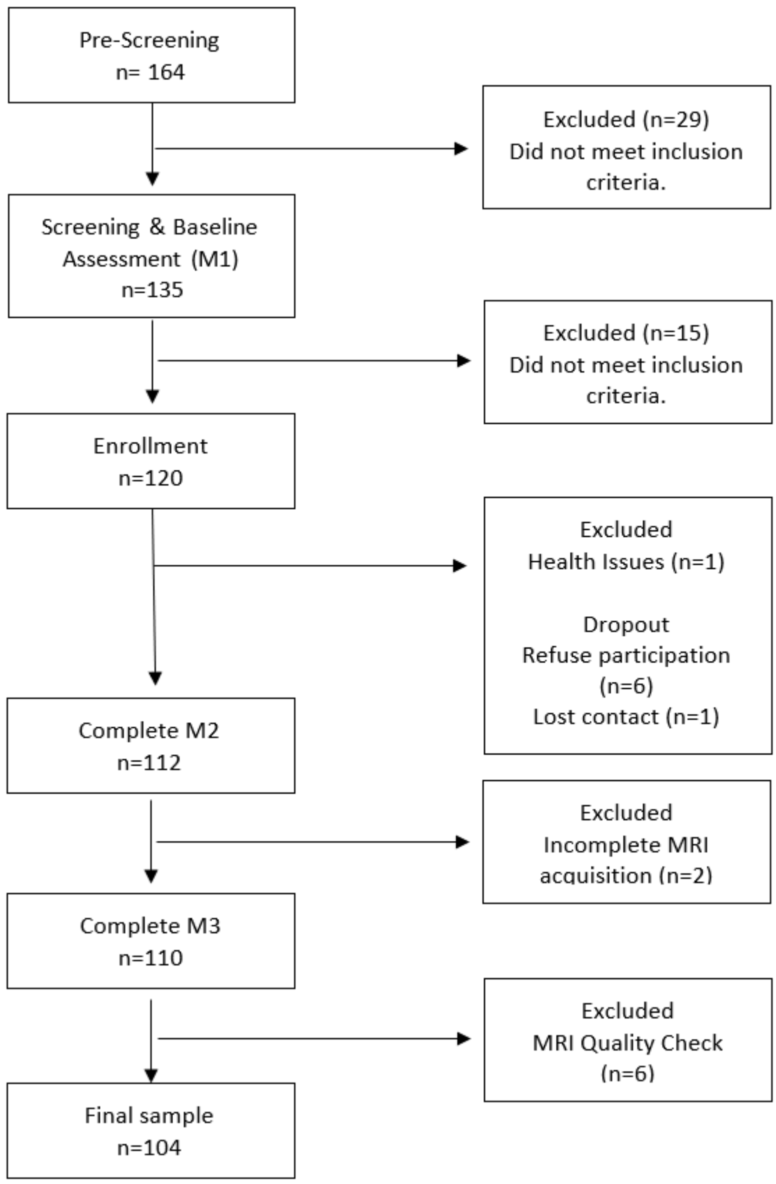

Figure 2. Flow diagram of participant screening and enrollment.

Table 1. General characteristics of the study participants (n=104).

Characteristics	N (%) or mean ± SD
Gender, n (%female)	58 (55.8)
Age, years	68.42 ± 3.12
Education, years	7.75 ± 5.28
Systolic BP (mmHg)	130.95 ± 15.42
BP (mmHg)	7.92 ± 11.87
HR	69.79 ± 10.81
Smoking status	
Current n (%)	10 (9.62)
Never n (%)	68 ± 65.38
Former n (%)	26 ± 25.00
Heavy smoker n (%)	10 ± 9.62
Alcohol consumption	
Alcohol drinker n (%)	75 ± 72.12
Excessive consumption n (%)	7 ± 6.73
Polypharmacy, n (%)	
< 3	80 ± 7.92
≥ 3	24 ± 23.08
Comorbidity Index	
0	12 ± 11,54
≥ 5	17 ± 16.35
Anthropometric	
Weight, Kg	73.59 ± 13.27
Height, m^2	159.58± 8.43
BMI, kg/m^2	28.83 ± 4.24
WHR	0.95 ± 0.07
Body composition	
FAT, %	33.70 ± 7.83
FFM, %	66.30 ± 7.83
Muscle, Kg	23.61 ± 4.24
Malnutrition Index	0.66 ± 0.05
Physical performance	
ADL score	5.66 ± 0.51
IADL score	7.97 ± 0.16
Balance score	15.57 ± 0.73
Gait score	11.97 ± 0.22
Max Right Grip, Kg	30.85 ± 10.11
Max Left Grip, Kg	29.47± 9.66
Speed, m/sec	64.91± 21.28

Abbreviations: BP blood pressure; HR heart rate, BMI, Body mass index; WC, waist circumference; HP, hip circumference; WHR, waist-to-hip ratio; FAT, Fat Mass; FFM, Free Fat Mass; Muscle, Muscle mass; ADL, Activities of Daily Living; IADL, Instrumental Activities of Daily Living.

Regarding the neuropsychological assessment, all participants presented values above the cut-off scores. The mean score for MMSE was 26.96 (SD±1.98) and 6.09 (SD± 4.56) for GDS. The cognitive variables are presented in Table 2.

Table 2. Neuropsychological characterization of the study participants (n=104).

Neuropsychologic characteristics	**mean ± SD**
MMSE	26.96 ± 1.98
GDS	6.09 ± 4.56
SRT-LTS	20.56 ± 13.34
SRT-CLTR	13.59 ± 12.37
SRT-DR	5,41 ± 2.59
Stroop-W	66.75 ± 19.72
Stroop-C	49.62 ± 10.65
Stroop-WC	26.11 ± 10.11
Stroop-golden	-2.01 ± 8.06
DSST score	32.54± 15.67
Digits Span Test	12.96 ± 3.72
COWAT FAS Admissible	21.96 ± 11.08

The SF-36 descriptive statistics for the eight scale domains and the two components (physical and mental health) are displayed in Table 3. The mean scores indicated a good health-related quality of life. The mean scores for PCS and MCS were 50.08 (SD ± 9.76) and 49.55 (SD ± 9.83), respectively.

Table 3. Descriptive statistics for SF-36 dimensions (n=104).

SF-36 domain	mean ± SD
Physical Functioning (PF)	86.88 ± 15.78
Role Physical (RP)	83.95 ± 23.07
Bodily Pain (BP)	44.47 ± 10.22
General Health (GH)	73.56 ± 17.16
Vitality (VT)	86.18 ± 16.19
Social Functioning (SF)	89.66 ± 17.72
Role Emotional (RE)	94.87 ± 12.74
Mental Health (MH)	89.57 ± 10.64
F-36 Component Scores	
Physical component summary (PCS)	50.08 ± 9.76
Mental component summary (MCS)	49.55 ± 9.83

Concerning Xiaomi Mi Band 2®-measured PA, the results showed that the median time spent in sedentary activities was 1296.27 min.day-1 (SD 106.99), light-intensity activity was 40.06 min.day-1 (SD 57.54), moderate-intensity was 17.24 min.day-1 (SD 18.32), and vigorous-intensity was 9.31 (SD 16.56). The data show that participants accumulated more time a day in light-intensity activities (Table 4).

Table 4. Descriptive PA data obtained from Xiaomi Mi Band 2® (n=104).

Characteristics	mean ± SD
Steps (steps.day^{-1})	
Light PA	3180.82 ± 4651.32
Moderate PA	1883,34 ± 1988.94
Vigorous PA	1263.68 ± 2311.07
Total Steps	9902.67 ± 8433.75
Time (min.day^{-1})	
Light PA	40.06 ± 57.54
Moderate PA	17.24 ± 18.32
Vigorous PA	9.31 ± 16.56
Total PA	143.73 ± 106.99
Sedentary time (min.day^{-1})	1296.27 ± 106.99

Furthermore, 56% of participants were physically active (somewhat active, n=27; active n=16; highly active, n=15) and 51% (n=53) were found to meet the guidelines of a minimum of 8000 steps/day (Table 5).

Table 5. Classification of older individuals according to PA Guidelines (n=104).

Characteristics	n (%)
Classification	
Sedentary	16 (15.4)
Low active	30 (28.8)
Somewhat active	27 (26.0)
Active	16 (15.4)
Highly active	15 ± 14.4
PA recommendation, n (%)	
Meeting PA	53 ± 51.0
Not meeting PA	51 ± 49.0

Voxel-based morphometry

Higher time spent vigorous PA was positively associated with hippocampal volumes when using the hippocampal mask (Figure 3). The significant peak voxels were found in the left parahippocampal gyrus and right hippocampus (Table 6).

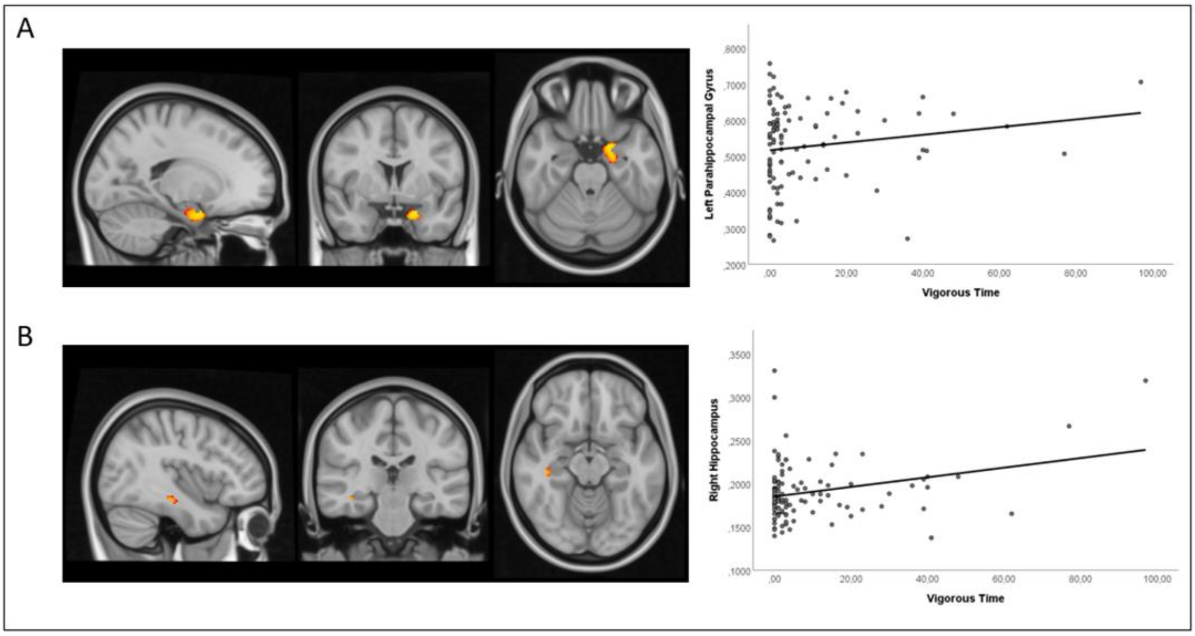

Figure 3. Sagittal, coronal, and axial view of the clusters and the scatter plot showing a significant positive correlation between vigorous time and: (A) left parahippocampal gyrus (-18, 2, -24) and (B) right hippocampus (40, -26, -14), after controlling for age, gender, age, MMSE, and GDS. All clusters illustrated were defined with a threshold at a p-value of 0.1.

Table 6. VBM results – Regression analysis of PA and brain volume (n=104).

Brain mask	Contrast	Effect direction	Ke	MNI Coordinates (x, y, z)	Region	Peak t-value
Hippocampus	Vigorous time	+	114	-18, 2, -24	Left parahippocampal gyrus	3.42
		+	6	40, -26, -14	Right hippocampus	4.43

Abbreviations: Ke, Cluster extent; MNI, Montreal Neurological Institute.

Network Based Statistics

Table 7 and Figure 4 show the networks identified using NBS with a significantly increased FC. The analysis revealed a significant increase in FC in a network involving nodes of the frontal cortex (superior gyrus #11, #12, frontal middle gyrus #14, and medial frontal gyrus #150), occipital inferior gyrus (#81 and #214), and cingulate gyrus (#15) was observed for light, moderate and total PA time, and for sedentary time. Moreover, the significant FC observed in the cerebellum limbic (parahippocampal gyrus #98) was specific for light and total PA time, and for sedentary time.

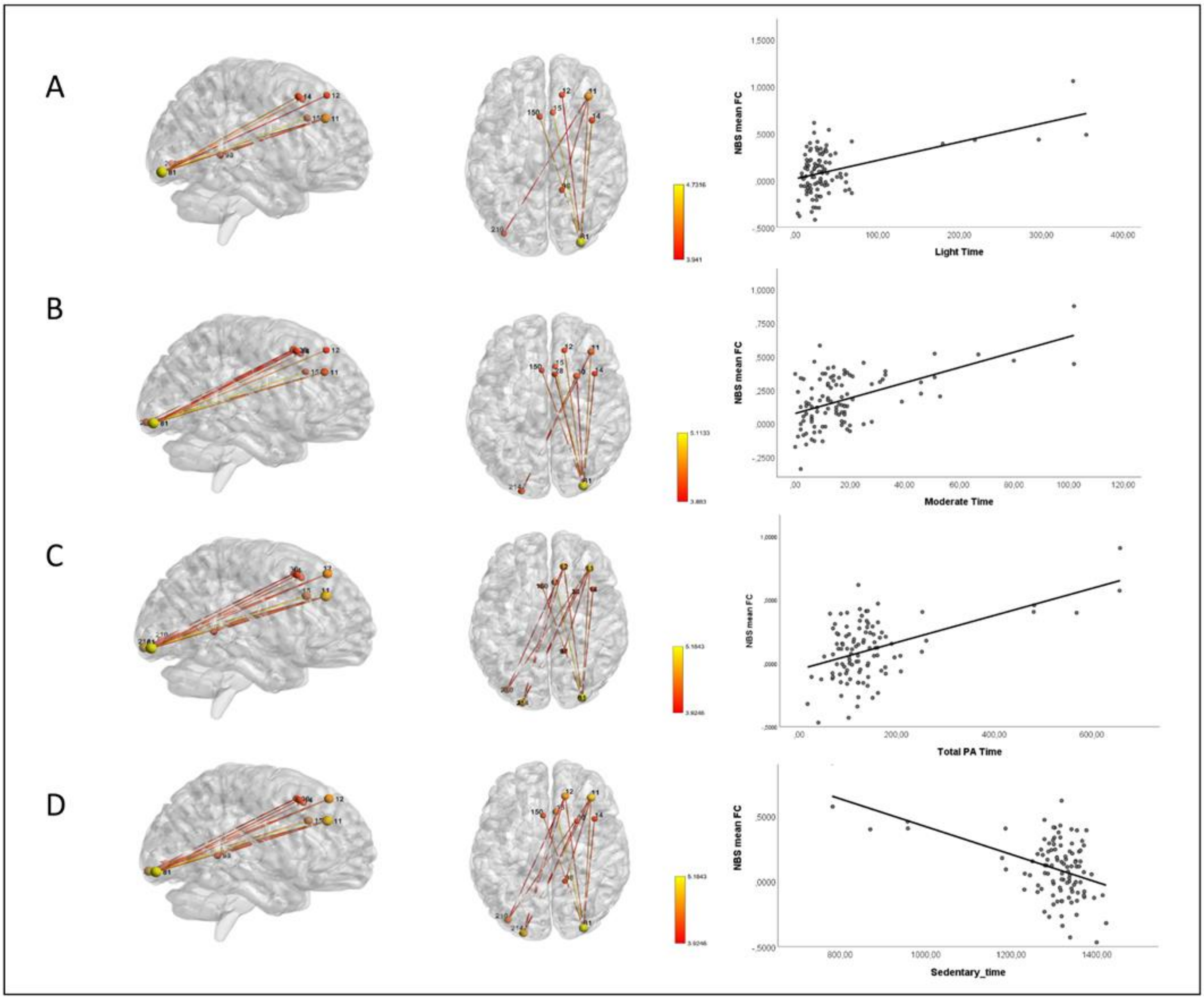

Figure 4. Networks of FC identified using NBS showing increased connectivity during rs-fMRI acquisition. Sagittal and axial view of the network with nodes and edges colored in red-yellow color scheme representing the statistical t-value and the scatter plot showing the relationships between the mean FC and: (A) light time; (B) moderate time; (C) total PA time; and (D) sedentary time; after controlling for age, gender, age, MMSE, and GDS.

Table 7. Results of the functional connectomics analysis using NBS (n=104).

Variable	Threshold (t,p)	Effect direction	*p*-value	R2	N. º Nodes	N. º Edges
Light time	(3,8631,1*10-4)	+	0.044	0.14	6	5
Moderate time	(3,8631, 1*10-4)	+	0.040	0.145	9	9
Moderate time	(4,055,5*10-5)	+	0.044	0.159	6	5
Moderate time	(4,4807, 1*10-5)	+	0.018	0.171	4	3
Total PA time	(3,8631, 1*10-4)	+	0.034	0.141	10	12
Total PA time	(4,055,5*10-5)	+	0.022	0.146	9	8
Sedentary time	(3,8631, 1*10-4)	-	0.031	0.1411	10	12
Sedentary time	(4,055,5*10-5)	-	0.026	0.1461	9	8

5. Discussion

Multiple neuroimaging studies have provided evidence that PA has protective effects on brain structure and function in older adults (C. Domingos, Pêgo, & Santos, 2020). However, the use of subjective measures of PA and the lack of a multimodal MRI approach have limited the understanding of this association. Therefore, in this study, we used objective PA data (obtained from a Xiaomi Mi Band 2) combined with neuroimaging acquisitions to test whether PA is related to the preservation of brain volume and better brain function in brain-healthy older adults (without neuropathological disease or dementia). The main findings from this study were as follows: (1) higher time spent in vigorous PA associated with larger volumes in left parahippocampal gyrus and right hippocampus; (2) light, moderate and total PA time associated with greater FC between the frontal gyrus (superior, middle, and medial), cingulate gyrus, occipital inferior lobe and parahippocampal gyrus, and (3) sedentary time associated with lower FC in the same networks.

The structural MRI results validated the findings from previous studies that show a consistent positive association between hippocampus and PA. Specifically, previous cross-sectional studies in older adults, using objective measures of PA, observed that a greater amount, duration, and frequency of total daily walking activity were associated with larger hippocampal volume (V. R. Varma, Chuang, Harris, Tan, & Carlson, 2015), and larger hippocampal surface area (Vijay R. Varma, Tang, & Carlson, 2016) in women, but not men. However, these previous results were specific for low-intensity activities in contrast to our results that were specific for moderate and vigorous activities. The association between hippocampus volume and PA was also noticed in cross-sectional studies in older adults using self-report PA measures (Hashimoto et al., 2017; Zlatar et al., 2015). In addition to the hippocampus, previous cross-sectional studies using objective measures of PA have shown the association with a lower volume of WMH (Burzynska et al., 2014), higher fractional anisotropy in the temporal lobe (Burzynska et al., 2014), and greater inferior and anterior temporal lobe volumes (Dougherty et al., 2016). Regarding longitudinal studies, other authors observed that the maintenance of time spent walking predicted less reduction in hippocampal volume 13 years later (Best et al., 2017), and greater walking distances associated with greater GM in the hippocampus 9 years later (K. I. Erickson et al., 2010).

To summarize, the finding of a positive association between higher time spent in vigorous PA with larger hippocampal volume is of particular relevance, since hippocampal atrophy is associated with cognitive decline, memory impairment, and dementia, and is a well-established neuroimaging biomarker in the preclinical stages of Alzheimer's disease (Arenaza-Urquijo et al., 2017; Hashimoto et al., 2017; V. R. Varma et al., 2015), and goes in hand with a recent systematic review suggesting that PA may also attenuate the age-related decline in brain regions vulnerable to dementia, including the hippocampus, temporal, and frontal regions (C. Domingos et al., 2020).

Regarding brain functional connectivity, the present results suggest that higher levels of moderate and total PA time are positively associated with increased functional connectivity in areas responsible for cognitive functions, particularly in working memory (du Boisgueheneuc et al., 2006), executive attention (Japee, Holiday, Satyshur, Mukai, & Ungerleider, 2015) decision-related processes (Talati & Hirsch, 2005), visuospatial processing and episodic memory (Aminoff, Kveraga, & Bar, 2013), regulation of motor function and processing emotions (Cera, Esposito, Cieri, & Tartaro, 2019) and visual processing (Fan, Wang, Shao, Zhang, & He, 2020). Furthermore, sedentary behavior was associated with decreased FC in the same brain areas. These results are in line with a recent systematic review that suggests a positive relationship between PA and executive function and memory performance (C. Domingos et al., 2020). Other cross-sectional studies in older adults have shown increased activation in BOLD response (famous > unfamiliar faces) in medial frontal gyrus/supplementary motor area, left precentral gyrus, middle/superior frontal gyrus, left middle/inferior temporal gyrus/angular gyrus/supramarginal gyrus/precuneus (J. C. Smith et al., 2011). A greater BOLD response in the right angular gyrus/lateral occipital cortex and left supramarginal gyrus (Zlatar et al., 2013), left hippocampus (Thielen et al., 2016) dorsolateral prefrontal cortex (Kimura, Yasunaga, & Wang, 2013), and greater FC between mPFC and left thalamus/right hippocampus and insula (Thielen et al., 2016), and greater FC between default-mode and amygdala/ hippocampus/ ventromedial prefrontal cortex and lower connectivity between default-mode and precentral gyrus/postcentral gyrus/supplementary motor cortex (Voss et al., 2016), was also observed.

This study adds to the literature by using objective measures of PA to determine its level and, thus, suppressing the limitation associated with self-report measures, in exploring the association between PA and brain function and structure in community-dwelling older individuals. The cohort was further well-characterized regarding clinical and lifestyle characteristics, anthropometric and body composition measures, physical performance, cognitive measures informative of broad cognitive domains, and quality of life assessment. Furthermore, we have an adequate sample size, giving us sufficient statistical power to explore the associations. Despite the this, several limitations should be noted. The study was conducted using a convenience sample, relatively homogenous in age and health, thus the participants may not represent of the general older population (in fact, the inclusion/exclusion criteria prevent, for instance, the inclusion of individuals with neuropathological/degenerative disease). This may lead to attenuation in correlations and can influence the strength or bias of the correlations among variables (Fabrigar, Wegener, MacCallum, & Strahan, 1999) and, therefore, findings must be validated in future research in a larger non-selected sample with a variety of age-related chronic conditions allowing the generalization of the results. However, the study includes participants in living at home/community without asking for any change in their daily life activities, thus enabling to assess individuals who are often excluded from clinic-based studies. A further limitation to consider is the cross-sectional and observational nature of the study; therefore, any causal or temporal association between the levels of PA and brain health cannot be inferred. Additionally, reverse causation must be considered, since individuals with better brain health may have a physically more active lifestyle. Important to mention is that although specifically ask to continue their normal routines, individuals could have modified their behavior, specifically in response to their awareness of being observed (Hawthorne effect). Finally, we observed an asymmetric distribution in the PA patterns, with the distribution being positively skewed. In fact, researchers in health and behavioral medicine, who study PA often use outcome variables that have a lower bound of zero and are positively skewed (Baldwin, Fellingham, & Baldwin, 2016). This result makes sense because it is expected that most older adults have lower levels of PA, with just a few having higher levels. Therefore, we considered that the more extreme values observed in figures 3 and 4 are not necessarily outliers and are likely important values to explore the question at hand. Moreover, since we have a considerate sample size and used non-parametric methods (that have no assumptions on the data distribution) to establish the association with the MRI findings these values are not only not problematic, but important to address the question. Nonetheless, future studies using stratified random sampling with respect to PA levels could provide valuable insights into the relationship between PA and brain health. In conclusion, study findings suggest that the maintenance of hippocampal volume in healthy older adults is specifically associated with time spent in moderate and vigorous PA activities. Moreover, moderate PA and total PA time specifically increase brain FC in the frontal gyrus cingulate gyrus, parahippocampal gyrus, and in cerebellum occipital inferior lobe which are related with several cognitive functions, including memory, executive function, motor functions, visual and emotions processing. Altogether, the study provides new insights regarding the association between brain health and PA throughout the aging process.

6. Data Availability Statement

The datasets generated for this study are available on request to the corresponding authors.

7. Ethics Statement

The study was conducted according to the Helsinki Declaration (59th Amendment), approved by the local ethical committees (Approval Number 42-2018), and the Portuguese Data Protection Authority (Approval Number 11286/2017) and developed in compliance with the new European General Data Protection Regulation. The study goals and assessments were explained during screening procedures. All participants provided written informed consent before study enrollment, which included consent to their data processing.

8. Author Contributions

CD: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

MPP: MRI Formal analysis, MRI Methodology, Writing – review & editing.

RM: MRI Formal analysis, MRI Methodology, Writing – review & editing.

MM: Neuropsychological evaluations.

NS: Funding acquisition, Supervision, Writing – review & editing.

NCS: Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing.

JMP: Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing.

All authors reviewed and approved the final version of the manuscript.

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11. Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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1. Discussion and future perspectives

To successfully address the challenges of the increase in life expectancy of the global population it is essential to improve the health status, wellbeing, and quality of life in older age. Numerous studies have indicated that regular PA is a key component of successful aging (Rolland, Abellan van Kan et al. 2010, Bherer, Erickson et al. 2013, Gopinath, Kifley et al. 2018). Nowadays, there is clear evidence that PA can help to delay the onset of many chronic lifestyle-related and non-communicable diseases (Macpherson, Teo et al. 2017, Gopinath, Kifley et al. 2018). More recently, a growing body of research is focusing on whether PA could also have a positive benefit on brain aging by exploring healthy brain aging as well as cognitive impairment and dementia (Lautenschlager, Cox et al. 2012, Bherer, Erickson et al. 2013, Macpherson, Teo et al. 2017). In fact, several studies have suggested that PA is a promising public health intervention to counteract age-related cognitive decline and brain matter loss (Rolland, Abellan van Kan et al. 2010, Benedict, Brooks et al. 2013, Bherer, Erickson et al. 2013). However, most of the studies investigating the effects of PA in brain structure and function in older adults rely on PA self-report questionnaires, with only a few having focused on wearable technologies among older adults to explore this association. Thus, one step towards fully clarifying the potential impact of PA on brain health is the objective and continuous monitoring of PA in combination with neuroimaging studies. Addressing the limitations of the previous studies, in this thesis, we provided new insights into the association between PA and brain health using a multimodal imaging approach combined with an objective measurement of daily PA.

There is a wide range of tools available for PA assessment, including subjective and objective measures, and it is unclear which tool should be used in older adults. Thus, in **Chapter I**, we compared accelerometer-based estimates of PA from Xiaomi Mi Band 2® with PA data obtained from self-report questionnaires. As expected, our results highlight a large variation between self-reported and Xiaomi Mi Band 2®-measured PA and sedentary time, and the general agreement between the measures was poor. The highest difference between objective and subjective methods was found for sedentary time. Moreover, we observed a poor to moderate correlation between self-reported estimates of PA and sedentary behavior. Therefore, given the inconsistency found between methods, there is an unquestionable need to implement PA standardization measures across studies to make them comparable. Furthermore, we think that the use of objective PA measures is highly recommended in older adults since self-reporting is more susceptible to recall bias due to the cognitive decline associated with normal aging. In addition, our findings highlighted that self-reported and objectively measured PA have different associations with health outcomes, probably because these are measuring different aspects of PA. Thus, we conclude that accelerometers and questionnaires could provide complementary information. However, there is a need for future studies to clarify why different types of measures associate differently with health outcomes (Prince, Cardilli et al. 2020). In addition, our study provided a valuable contribution to the field by describing the PA levels in a sample of community-dwelling Portuguese older adults, since there is a lack of knowledge about the PA and sedentary behaviors among the older adults (Lohne-Seiler, Hansen et al. 2014). The results have shown that there were no gender differences in total minutes per day spent in all PA intensities for objective assessment. Nevertheless, we found a significant difference for self-reported PA levels between genders, with higher values for women. Consequently, the differences between genders seem to influence these estimates only for self-reported PA and should be explored in future studies. To summarize, accurate assessment of PA is essential for interventions promoting PA. Our study provided valuable insight regarding accelerometer measurements in the senior population, contributing to the future implementation of this wearable technology.

Chapters II and **III** focused on the use of wearable technologies among older adults. Specifically, in **Chapter II** we conducted a transcultural adaptation and validation of a questionnaire that can be used to evaluate, in older adults, the user satisfaction with several mHealth technologies. User satisfaction is an important usability component that represents the user's attitude towards the system and affects the behavior intention of use (Harrison, Flood et al. 2013, He, Kim et al. 2017, Chao 2019). Our results demonstrate that our adapted questionnaire, with psychometric properties consistent with the original version, is a valid and reliable tool for measuring user satisfaction with activity trackers in older adults. Thus, with this study, we provided a simple and easy-to-understand questionnaire that could be used in future studies. Furthermore, we tested the user satisfaction with Xiaomi Mi Band®, and observed an excellent reported level of satisfaction. This suggests that this activity tracker is suitable for older adults, ensuring that it can be successfully implemented in clinical and research settings. In addition, our study extended the knowledge regarding user satisfaction with wearable technologies among older adults, although there is still a need for more studies, including studies evaluating long-term satisfaction. Finally, this is an interesting area for future research, since if the user experience is pleasant and satisfactory probably the users will adopt the device for long-term use. This is of particular interest to the senior population since these devices could be valuable in strategies that aimed to promote PA with its health benefits.

In **Chapter III** we performed an exploratory study to evaluate the acceptability, usability, and user satisfaction with Xiaomi Mi Band 2® in a real-world context. Regarding user satisfaction, we used the questionnaire previously validated in **Chapter II**. Overall, our results have shown a very high user acceptance, while other authors found a moderate acceptance for Xiaomi Mi Band (Puri, Kim et al. 2017). The findings also reveal excellent usability for this wearable device and user satisfaction was classified as a good experience. Therefore, our study suggested that Xiaomi Mi Band is a feasible tool for measuring PA in older adults in a real-world context. Despite this conclusion, we did not account for the participant's intrinsic and extrinsic motivations and the long-term perceptions, which could influence the results. Moreover, we observed that usability is a significant predictor of user satisfaction. Additionally, our model also showed that individual characteristics, in particular depression symptoms, seem to be an important predictor of usability perception and user satisfaction. We also found that the indirect effect of usability on user satisfaction was higher in individuals with lower GDS levels and higher MMSE levels, and only had a significant effect on older adults with lower education. Together, the present findings extend the existing knowledge in wearable activity trackers in older adults and reinforce that acceptability, usability, user satisfaction, and user characteristics are critical factors to determine older users' technology acceptance behavior. Finally, since wearable activity trackers have the potential to promote PA with its health benefits, including brain health (**Chapter IV** and **Chapter V**), and it is known that older adults may experience usability barriers to technology adoption, there is a need for more studies evaluating the user experience in this population to understand the older adults' difficulties, which should be noticed by manufacturers.

Chapter IV provides a systematic review of the literature exploring cross-sectional and longitudinal neuroimaging MRI studies that have examined the relationship between PA and brain structure and function in older adults without cognitive or neuropathological disease. This review was an important contribution to the field since it allowed the integration of information about this relationship and highlighted the importance of maintaining regular PA (even low-intensity activities) as a strategy to prevent neurodegenerative diseases. Particularly, the results demonstrated that PA was associated with larger brain volumes in the hippocampus, temporal, and frontal regions. Moreover, the fMRI studies revealed a greater task-relevant activity in regions of the brain that support executive function and memory tasks. Interestingly, the protective effects of PA appear to be greater in healthy older adults at genetic risk for dementia. Despite this evidence, we found a lack of consensus in PA definition and measurements, which makes it challenging to determine what are the PA recommendations for better brain health in older adults. Therefore, future research should focus on a more accurate PA definition, standardized PA measurements as well as the optimal dose of it for succeeding a healthy brain aging. Additionally, this review also demonstrated that most previous studies focused on subjective measures of PA such as self-report questionnaires, whose validity in measuring the activities of daily living is limited (Erickson, Leckie et al. 2014, Tian, Glynn et al. 2015). Nonetheless, wearable tracking technologies are recently becoming popular among researchers interested in assessing PA-related behavior (addressed in **Chapter III**), allowing the opportunity to collect objective and precise assessment of everyday activities, including non-exercise lifestyle activities and sedentary behavior in real-time (Rupp, Michaelis et al. 2018, Turner-McGrievy, Jake-Schoffman et al. 2018, Alley, van Uffelen et al. 2019). Lastly, due to the heterogeneity in PA measures across the studies we were not able to establish the dose-response relationship that is associated with better brain health, neither establishment of PA recommendation. Therefore, further research using objective PA measures is crucial to establish which PA intensity, frequency, and duration, as well as PA type, have the greatest protective effect on brain health.

Finally, in **Chapter V** we explored the associations between PA and brain structure and function using a wearable activity tracker to measure and quantify free-living PA in older adults. This study goes beyond previous research, through the use of a multimodal imaging approach combined with an objective measurement of daily PA, suppressing the previous limitations in the literature described in detail in **Chapter IV**. Our findings indicate that the maintenance of hippocampal volume specifically in the left parahippocampal gyrus and right hippocampus in healthy older adults is associated with higher time spent in vigorous PA activities. Furthermore, fMRI results suggest that moderate PA and total PA time increase brain FC in regions associated with several cognitive functions, including memory, executive function, motor functions, visual and emotional processing. Still, although the study provided new insights regarding the PA benefits on brain health, we were not able to identify which dose of PA, considering the components of intensity, duration, or both, is necessary to preserve brain health through older age.

Therefore, future studies are essential to establish recommendations regarding PA and to explore pathways that promote the effect of PA on the brain and cognition. Furthermore, the proposed relationships need to be tested in longitudinal observational or intervention studies. Additionally, it remains to be determined whether the benefits extend to older adult samples aged 80 and above. Ultimately, it will be useful to explore the interactive effects of cognitive and health status variables with this relationship.

Finally, future research should implement standard concepts, metrics, measures, and approaches to evaluate the effects of PA on healthy brain aging to facilitate comparisons among different cohorts and studies. Standardized protocols will allow the establishment of the optimal PA dose for succeeding in healthy brain aging. Furthermore, high-quality randomized controlled trials and meta-analyses addressing the measurement issues are needed to determine the relationship between brain changes induced by PA and cognitive performance in older adults. In addition, future studies might further investigate the mechanisms underlying the PA effect on brain health.

2. Conclusion

Recent evidence suggests that PA could be a nonpharmacologic therapeutic approach to prevent the development of age-related diseases, delay the onset of cognitive decline, and protect against dementia. In addition, research has shown that wearable devices have the potential to promote the adoption of a physically active lifestyle. In particular, our study has demonstrated that the Xiaomi Mi Band® is a feasible and suitable wearable activity tracker that can be used in older adults, presenting high levels of technology adoption and an excellent level of usability and satisfaction. Furthermore, this device proved to be an accurate tool to determine PA levels, being more precise in the estimation of sedentary behavior compared to self-report questionnaires. Thus, we concluded that Xiaomi Mi Band® may be a useful tool to successfully be used in PA interventions in older adults.

Ultimately, our structural MRI findings highlight the protective effects of PA in the hippocampus and the fMRI functional results indicated a positive effect on several cognitive functions. Therefore, with this thesis we contributed to the knowledge regarding the effects of PA on brain health throughout the aging process, supporting the previous evidence in the literature.

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APPENDIX A

Ethics committee approval - University of Minho

Universidade do Minho

SECVS

Subcomissão de Ética para as Ciências da Vida e da Saúde

Identificação do documento: SECVS 014/2018

Título do projeto: *Caracterização de um sistema de monitorização de atividade física como substituto da estrutura e função do cérebro em idosos*

Investigador(a) responsável: Célia Margarida Viegas Domingos, do Instituto de Investigação em Ciências da Vida e da Saúde (ICVS) e do ICVS/3B's - Laboratório Associado

Subunidade orgânica: Instituto de Investigação em Ciências da Vida e da Saúde (ICVS) e do ICVS/3B's - Laboratório Associado, Escola de Medicina, Universidade do Minho

Outras Unidades: Unidades de Saúde Familiar (USF), lares, centros de dia, ginásios e Universidades sénior na região de Braga

PARECER

A Subcomissão de Ética para as Ciências da Vida e da Saúde (SECVS) analisou o processo relativo ao projeto intitulado *Caracterização de um sistema de monitorização de atividade física como substituto da estrutura e função do cérebro em idosos.*

Os documentos apresentados revelam que o projeto obedece aos requisitos exigidos para as boas práticas na experimentação com humanos, em conformidade com o Guião para submissão de processos a apreciar pela Subcomissão de Ética para as Ciências da Vida e da Saúde.

Face ao exposto, a SECVS nada tem a opor à realização do projeto.

Braga, 28 de maio de 2018.

A Presidente

MARIA CECÍLIA DE LEMOS PINTO ESTRELA LEÃO

Assinado de forma digital por MARIA CECÍLIA DE LEMOS PINTO ESTRELA LEÃO
Dados: 2018.05.29 09:46:06 +01'00'

Maria Cecília de Lemos Pinto Estrela Leão

Universidade do Minho

SECVS

Identificação do documento: SECVS 014/2018

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Outras Unidades: Unidades de Saúde Familiar (USF), lares, centros de dia, ginásios e Universidades sénior na região de Braga

Data de receção na SECVS: 14 de março de 2018

Grelha de Verificação

Processo submetido em suporte: [X] eletrónico [ ] físico (em papel)

Documentos	Sim	Não	Não se aplica
Requerimento e/ou ofício e/ou pedido de apreciação de projeto [a) b)]	X		
Informação do Responsável pela Unidade/Diretor de Serviço sobre apoio e/ou enquadramento/cabimento do projeto na Unidade/Serviço em que decorrerá [a) b)]	X		
Protocolo do estudo, incluindo, se aplicável, os instrumentos de recolha de dados e/ou informação para o participante [a) b)]	X		
Curriculum Vitae abreviado do Investigador Responsável [a) b)]	X		
Modelo de Consentimento Informado [a) b)]	X		
Modelo de Declaração de Compromisso de Confidencialidade	X		
Informação sobre financiamento para o cumprimento do projeto, incluindo, se aplicável, cabimento/inscrição no orçamento da Unidade/Serviço em que decorrerá e/ou com fonte de financiamento nacional/internacional	X		
CESHB – Remitir processo: Sim [ ] Não [X]			
Requerimento dirigido ao Presidente da CESHB [b)]		X	
Formulário da CESHB devidamente preenchido [b)]		X	
Outros			
Autorizações e/ou Pareceres de (Sub)Comissões de Ética	X		
Acordo Financeiro	X		

Apólice de Seguro	X		
Informação do Orientador da Tese sobre apoio e/ou enquadramento do projeto	X		

[a] Documentos obrigatórios de acordo com as normas orientadoras para submissão de processos a apreciar pela SECVS em Anexo ao Despacho RT-76/2012 que estabelece as regras de atuação e funcionamento da mesma.
[b] Documentos obrigatórios de acordo com o funcionamento da Comissão de Ética para a Saúde do Hospital de Braga (CESHB).

Justificação do Parecer

Trata-se de um estudo efetuado no âmbito de Projeto de Doutoramento da investigadora Célia Margarida Viegas Domingos, orientada por Nadine Correia Santos, PhD e José Miguel Pêgo, MD, PhD, na Escola de Medicina da Universidade do Minho.

O apoio financeiro ao estudo é providenciado por fundos FEDER pelo *Operational Program Competitiveness Factors* - COMPETE e por fundos nacionais pela *Foundation for Science and Technology* - FCT pelo projeto POCI-01-0145- FEDER-007038; e pelo projeto NORTE-01-0145-FEDER-000013, apoiado pelo Norte Portugal Regional Operational Program (NORTE 2020), através do programa PORTUGAL 2020 - *Partnership Agreement, pelo European Regional Development Fund* (ERDF). Especificamente o estudo tem sido apoiado pelos projetos "*SwitchBox – Maintaining health in old age through homeostasis*" (Contrato HEALTH-F2-2010-259772; Comissão Europeia, FP7)", "TEMPO - *Better mental health during ageing based on temporal prediction of individual brain ageing trajectorie*s" (Contrato P-139977; Fundação Calouste Gulbenkian) e "PANINI - *Physical Activity and Nutrition INfluences In ageing*" (Contrato GA 675003; Comissão Europeia, H2020).

Não são previstos quaisquer custos, ou abuso de recursos institucionais, hospitalares e/ou outros para a realização do projeto. Não serão implicados custos ao participante e não haverá qualquer ressarcimento ou remuneração, sendo que despesas de deslocação e alimentação, se necessário, serão cobertas pelo projeto.

Trata-se de um estudo com o apoio institucional do Laboratório Associado ICVS/3B's, do 2CA-Braga e do ACES Cavado I – Braga.

Os dados a recolher consistem em: idade/data de nascimento; género; dados antropométricos; sinais vitais; composição do agregado familiar sem identificação dos membros; dados da história clínica; dados dados de exame físico; dados de meios complementares de diagnóstico; medicação prévia concomitante; dados de qualidade de vida/efeitos psicológicos; comportamentais, psicológicos ou volitivos com conexão com a Investigação.

O projeto recebeu parecer favorável da comissão de ética da ARS Norte, em 6 de Março de 2018, e aprovação da Comissão Nacional de Protecção de Dados (CNPD) (Autorização Nº 11286/ 2017), em 9 de Outubro de 2017.

O objetivo geral deste projeto consiste na caracterização de um sistema de monitorização da atividade física em idosos avaliando a usabilidade, viabilidade desempenho do sistema e a posterior correlação entre padrões de atividade física e estrutura e função do cérebro, com recurso a estudos de neuroimagem.

Os objetivos específicos pretendem:

1. Avaliar a usabilidade e viabilidade do sistema de monitorização de atividade física em idosos;
2. Monitorização e correlação da atividade física com a estrutura e função cerebral em idosos;
3. Avaliar se o uso do sistema de monitorização de atividade física com feedback mediado por telefone pode modificar os padrões de uso do sistema e o comportamento relativamente às atividades físicas diárias.

Trata-se observacional transversal para primeiro e segundo objetivos. O último objetivo do projeto será um estudo longitudinal com um desenho experimental pré-pós intervenção.

Pretende recrutar 120 participantes: homens e mulheres com 65-75 anos de idade e com capacidade de participar nas sessões de avaliação. O recrutamento dos participantes será feito nas Unidades de Saúde Familiar (USF), lares, centros de dia, ginásios e Universidades sénior na região de Braga.

Os participantes dos Cuidados de Saúde Primários poderão ser convidados através do médico de família encaminhando-os para a investigadora de forma prospetiva (caso apresente critérios à data da consulta com o médico assistente) ou de forma retrospetiva (através de consulta do historial clinico do utente), neste caso, com contacto prévio dos Serviços Administrativos da Unidade de Saúde, a dar conhecimento do estudo e a perguntar se estão interessados em participar, em caso afirmativo perguntar se podem dar o contacto telefónico à investigadora. Só após a anuência do utente é possível fornecer ao investigador o contacto.

O processo de recolha de informação será efetuado em 5 momentos de avaliação. A avaliação neuropsicológica será efetuada por psicólogos com experiência na recolha da informação na população em questão. As restantes avaliações serão efetuadas pelo investigador através de questionários. A exposição dos participantes será efetuada através da aplicação dos seguintes questionários:

a) Questionário sociodemográfico;
b) Questionário de avaliação clínica;

c) Avaliação antropométrica (ex: altura, peso, perímetros, etc.);

d) Avaliação neuropsicológica: o Mini-Exame do Estado Mental (MMSE) será utilizado para verificar a função cognitiva no global e o escala da depressão geriátrica (GDS) para avaliar o humor depressivo; o teste *Digit Span* (subtest do teste Wechsler de inteligência para adultos (WAIS III)) será usado como uma medida de memória operacional, memória de curto prazo e atenção A prova de cor e palavra *Stroop* será usada para testar a capacidade de resistir à interferência e avaliar a flexibilidade cognitiva e o controle inibitório. O *Selective reminding test* (SRT) será utilizado para avaliar a aprendizagem verbal e a memória.

e) Avaliação habilidade funcional (autonomia física e autonomia instrumental) Questionário de Habilidade Funcional (*Questionnaire of Functional Ability*, QFA), Escala de Atividades de Vida Diárias (Katz Index), Atividades Instrumentais de Vida Diárias de Lawton & Brody (IADL), Avaliação da mobilidade e equilíbrio estático e dinâmico (POMA-1 | Tinetti Test), Teste da caminhada de seis minutos, Teste da força muscular dos membros superiores, Teste de força de membros inferiores;

f) Avaliação da atividade física: Questionário de atividade física - versão longa (IPAQ) e questionário YPAS (*International Physical Activity Questionnaire*);

g) Avaliação da qualidade de vida Questionário de estado de saúde (SF-36);

h) Avaliação da usabilidade e aceitação do dispositivo de monitorização: questionário TAM 3 (*The technology acceptance model 3*), questionário SUS (*System Usability Scale*); questionário USEQ (*The User Satisfaction Evaluation Questionnaire*).

Para além dos questionários os participantes serão monitorizados através do uso de um dispositivo de monitorização de atividade física e serão ainda sujeitos a Ressonância Magnética Estrutural e Funcional do cérebro.

Pretende-se finalizar o estudo em janeiro de 2020.

<u>Considerações éticas</u>

1. O anonimato dos dados está garantido e a participação assegurada através de declaração de consentimento informado.
2. O modelo de consentimento informado cumpre com os requisitos éticos adequados ao projeto
3. O risco de dano para os participantes é mínimo e o benefício social e científico considerado relevante.
4. Está garantido financiamento e o uso responsável e racional dos recursos para a investigação.
5. Reconhece-se a este estudo originalidade, relevância e pertinência dos resultados.

A realização de projetos de investigação deverá em consideração as regras de conduta e diretivas de boas práticas no âmbito da investigação clínica com seres humanos. Deverá ser solicitado Parecer e/ou Autorização, incluindo notificação de tratamento de dados pessoais à Comissão Nacional de Proteção de Dados, e seguir as diretivas nacionais e/ou locais, de cada lugar de recolha, como aplicável, incluindo de Unidades Hospitalares e/ou Unidades de Saúde onde será realizado o estudo, e/ou onde serão recolhidas as amostras e/ou dados e/ou aplicados os questionários, se aplicável.

Salienta-se o respeito pelas normas e as recomendações constantes da Declaração de Helsínquia (com as emendas de Tóquio 1975, Veneza 1983, Hong-Kong 1989, Somerset West 1996, Edimburgo 2000, Washington 2002, Tóquio 2004 e Seul 2008), da Directiva 95/46/EC do Parlamento Europeu e do Conselho, das Directrizes Sobre as Boas Práticas Clínicas da EMEA - Agência Europeia do Medicamento (Londres 2000), das Directrizes Éticas Internacionais para a Pesquisa Envolvendo Seres Humanos da Organização Mundial de Saúde (Genebra 2002), das Directrizes Éticas Internacionais para os Estudos Epidemiológicos do Conselho de Organizações Internacionais de Ciências Médicas (Genebra 2009) e da Resolução da Assembleia da República nº1/2001.

Quando aplicável o Consentimento Informado recomenda-se as normas e/ou documentos-guia da Direção Geral de Saúde[1] e/ou da ARS Norte[2] na elaboração do mesmo. A inclusão dos participantes em qualquer um dos âmbitos de investigação considerados num Projeto de Investigação está subjacente o seu consentimento escrito (Lei n.º 12/2005, de 26 de Janeiro; Lei n.º 46/2007, de 24 de Agosto). O preenchimento e assinatura do formulário de consentimento informado, livre e esclarecido, deverá ser feito em duplicado, garantindo a privacidade e confidencialidade dos dados pessoais e o direito a recusar/abandonar o estudo sem sofrer qualquer penalização.

Indica-se que recolha de produtos biológicos deverá ter em conta os princípios para obtenção e conservação de material biológico (Art. 18.º) da Lei 12/2005 de 26 de janeiro. O tratamento das informações de saúde recolhidas terá em consideração os princípios aplicáveis aos tratamentos de dados pessoais efetuados no âmbito de Investigação Clínica, definidos pela Comissão Nacional de Proteção de Dados e decorrentes da Deliberação nº 1704/2015.

Informações pessoais tratadas não deverão ser identificáveis, mas sim irreversivelmente anonimizadas (Art. 3.º da LPDP), e todos os dados obtidos no âmbito de um Projeto de Investigação estão ao abrigo de medidas técnicas e organizativas adequadas que dão cumprimento ao disposto no Art. 14.º e Art. 15.º da LPDP. Aplica-se ainda o disposto no n.º1 do Art. 17º da LPDP relativamente ao sigilo profissional. Quando não for possível a anonimização dos dados, estes deverão codificados de acordo com uma chave específica, acessível apenas aos

[1] http://www.dgs.pt/directrizes-da-dgs/normas-e-circulares-normativas/norma-n-0152013-de-03102013.aspx

[2] http://portal.arsnorte.min-saude.pt/portal/page/portal/ARSNorte/Comiss%C3%A3o%20de%20%C3%89tica/Ficheiros/Consentimento_Informado_Doc_Guia.pdf

investigadores do estudo, e que dificulta a identificabilidade dos participantes, tal como especificado na Deliberação nº 1704/2015 da CNPD. Os dados obtidos deverão ser conservados de forma a permitir a identificação dos seus titulares apenas durante o período necessário para a prossecução das finalidades da recolha ou do tratamento posterior, tal como definido no Art. 5.º, n.º 1, alínea e), da LPDP.

O Modelo de declaração de compromisso e confidencialidade utilizado pelo IR deverá ser seguido e assinado por outros investigadores ou colaboradores na investigação, conforme aplicável, destinado a documentar o seu envolvimento nas garantias de confidencialidade e boas praticas dadas pelo(a) IR Sempre que necessário, os membros da equipa de investigação deverão assinar uma Declaração de Interesses e Incompatibilidades de acordo com o Decreto-lei n.º14/2014, de 22 de janeiro.

Neste contexto, assume-se que os investigadores que trabalham com amostras humanas, ou com a análise de dados, estão obrigados a manter sigilo profissional sobre os dados pessoais e sobre os resultados ou demais obtidos, segundo a ética profissional, nunca devendo, por isso, fazer uso dos mesmos a não ser para o fim a que se destinam. Esta obrigação mantém-se em efeito após término do projeto de investigação.

Documentos recebidos na SECVS

O processo foi acompanhado por requerimento dirigido à Presidente da SECVS.

A SECVS recebeu os documentos comprovativos que incluem:

- Protocolo de investigação e/ou caderno de recolha de dados e/ou guião da entrevista;
- Curriculum vitae abreviado do(s) investigador(es) responsável(eis);
- Parecer do(a) diretor(a) do centro de investigação e/ou unidade;
- Modelo de documento de consentimento informado;
- Cópia do(s) formulário(s) de recolha de dados a utilizar e/ou enumeração dos dados que serão colhidos.

Foram ainda recebidos (outros documentos):

- Curriculum vitae abreviado do(a)(s) aluno(a)(s);
- Modelo de declaração de compromisso a utilizar pelo(a) PI e por outros investigadores ou colaboradores na investigação destinado a documentar o seu envolvimento nas garantias de confidencialidade e boas praticas dadas pelo(a) PI (Termo de Responsabilidade);
- Guião de questionário;
- Declaração de interesses e incompatibilidades;
- Declaração do orientador no compromisso na orientação e/ou Termo de Responsabilidade.

Os documentos enviados estão em conformidade com o Guião para submissão de processos a apreciar pela Subcomissão de Ética para as Ciências da Vida e da Saúde (SECVS).

Face ao exposto, a SECVS nada tem a opor à realização do projeto.

Braga, Universidade do Minho, 28 de maio de 2018

A Presidente

MARIA CECÍLIA DE LEMOS PINTO ESTRELA LEÃO

Assinado de forma digital por MARIA CECÍLIA DE LEMOS PINTO ESTRELA LEÃO
Dados: 2018.05.29 09:49:47 +01'00'

Maria Cecília de Lemos Pinto Estrela Leão

APPENDIX B

Ethical committee approval – ARS Norte

ARS NORTE
Administração Regional
de Saúde do Norte, I.P.

ADMINISTRAÇÃO REGIONAL DE SAÚDE DO NORTE, IP
EXARADO NA ACTA Nº 11
REUNIÃO DE 2018.03.09

DELIBERADO CONCORDAR
2018/03/09

Dr. Pimenta Marinho
Presidente do C.D.

Rita Moreira
Vice-Presidente do CD

Paula Duarte
Vogal do CD

Dr. Ponciano Oliveira
Vogal C.D.

☐ ☐ ☐ DATA : 8.março.2018

INFORMAÇÃO Nº 048/2018 Nº <Processo> <Registo>

PARA: Conselho Diretivo da ARS Norte

DE: Comissão de Ética para a Saúde da ARS Norte

ASSUNTO: Parecer nº 42/2018

Levo ao conhecimento do Conselho Diretivo o Parecer nº 42/2018 sobre o Estudo "Caraterização de um sistema de monitorização de atividade física como substituto da estrutura e função do cérebro em idosos", aprovado na reunião de 6 de março de 2018, por unanimidade.

À consideração superior

Ana Paula Capela
(Assessoria CES/UIC)

Rua Santa Catarina, 1288 4000-447 Porto Tel 220 411 000 Fax 220 411 005 arsn@arsnorte.min-saude.pt www.arsnorte.min-saude.pt

02

Comissão de Ética para a Saúde

Administração Regional de Saúde do Norte, IP

PARECER Nº 42/2018

Sobre o estudo T868 - CARACTERIZAÇÃO DE UM SISTEMA DE MONITORIZAÇÃO DE ATIVIDADE FÍSICA COMO SUBSTITUTO DA ESTRUTURA E FUNÇÃO DO CÉREBRO EM IDOSOS.

A – RELATÓRIO

A Comissão de Ética para a Saúde (CES) da Administração Regional de Saúde do Norte, I.P. (ARSN) iniciou, a apreciação do Processo T868, com o título supra, AUTOR Célia Margarida Viegas Domingos AFILIAÇÃO: Instituto de Ciências da Vida e da Saúde (ICVS) ORIENTADO Nadine Correia Santos, PhD AFILIAÇÃO: Instituto de Ciências da Vida e da Saúde (ICVS) ORIENTADO José Miguel Pêgo, MD, PhD AFILIAÇÃO: Instituto de Ciências da Vida e da Saúde (ICVS)

1. Integram o processo os seguintes documentos: o protocolo de investigação com cronograma, questionários, as declarações de compromisso de confidencialidade e anonimato e de utilização dos dados apenas neste estudo, a declaração da entrega a esta CES de uma cópia do relatório final do projeto, os currículos *vitae* da Investigadora, parecer da Comissão Nacional de Proteção de Dados, declarações dos orientadores do estudo e consentimento informado livre e esclarecido.
2. O objetivo geral deste projeto consiste na caracterização de um sistema de monitorização da atividade física em idosos avaliando a usabilidade, viabilidade e desempenho do sistema e a posterior correlação entre padrões de atividade física e estrutura e função do cérebro, com recurso a estudos de neuroimagem. Os Objetivos específicos pretendem avaliar a usabilidade e viabilidade do sistema de monitorização de atividade física em idosos; Monitorização e correlação da atividade física com a estrutura e função cerebral em idosos e avaliar se o uso do sistema de monitorização de atividade física com feedback mediado por telefone pode modificar os padrões de uso do sistema e o comportamento relativamente às atividades físicas diárias.
3. Trata-se observacional transversal para primeiro e segundo objetivos. No último objetivo do projeto será um estudo longitudinal com um desenho experimental pré-pós intervenção. Pretende recrutar 120 participantes: homens e mulheres com 65-75 anos de idade e com capacidade de participar nas sessões de avaliação. O recrutamento dos participantes será feito nas Unidades de Saúde Familiar (USF), lares, centros de dia, ginásios e Universidades sénior na região de Braga. Os participantes dos Cuidados de Saúde Primários poderão ser convidados através do médico de família encaminhando-os para a investigadora de forma prospetiva (caso apresente critérios à data da consulta com o médico assistente) ou de forma retrospetiva (através de consulta do historial clínico do utente), neste caso, com contacto prévio dos Serviços Administrativos da Unidade de Saúde, a dar conhecimento do estudo e a perguntar se estão interessados em participar, em caso afirmativo perguntar se podem dar o

contacto telefónico à investigadora. Só após a anuência do utente é possível fornecer ao investigador o contacto. O processo de recolha de informação será efetuado em 5 momentos de avaliação: 1. A avaliação neuropsicológica será efetuada por psicólogos com experiência na recolha da informação na população em questão. As restantes avaliações serão efetuadas pelo investigador através de questionários. A exposição dos participantes será efetuada através da aplicação dos seguintes questionários: a) Questionário sociodemográfico; b) Questionário de avaliação clínica; c) Avaliação antropométrica (ex: altura, peso, perímetros, etc.); d) Avaliação neuropsicológica: o Mini-Exame do Estado Mental (MMSE) será utilizado para verificar a função cognitiva no global e o escala da depressão geriátrica (GDS) para avaliar o humor depressivo; o teste Digit Span (subtest do teste Wechsler de inteligência para adultos (WAIS III)) será usado como uma medida de memória operacional, memória de curto prazo e atenção. A prova de cor e palavra Stroop será usada para testar a capacidade de resistir à interferência e avaliar a flexibilidade cognitiva e o controle inibitório. O Selective reminding test (SRT) será utilizado para avaliar a aprendizagem verbal e a memória. e) Avaliação habilidade funcional (autonomia física e autonomia instrumental): Questionário de Habilidade Funcional (Questionnaire of Functional Ability, QFA), Escala de Atividades de Vida Diárias (Katz Index), Atividades Instrumentais de Vida Diárias de Lawton & Brody (IADL), Avaliação da mobilidade e equilíbrio estático e dinâmico (POMA-1 | Tinetti Test), Teste da caminhada de seis minutos, Teste da força muscular dos membros superiores, Teste de força de membros inferiores; 9 f) Avaliação da atividade física: Questionário de atividade física - versão longa (IPAQ) e questionário YPAS (International Physical Activity Questionnaire); g) Avaliação da qualidade de vida: Questionário de estado de saúde (SF-36); h) Avaliação da usabilidade e aceitação do dispositivo de monitorização: questionário TAM 3 (The technology acceptance model 3), questionário SUS (System Usability Scale); questionário USEQ (The User Satisfaction Evaluation Questionnaire); Para além dos questionários os participantes serão monitorizados através do uso de um dispositivo de monitorização de atividade física e serão ainda sujeitos a Ressonância Magnética Estrutural e Funcional do cérebro.

B – Identificação das questões com eventuais implicações éticas

1. Os custos do estudo, são da responsabilidade da investigadora
2. Não há indícios de exploração dos participantes
3. Está garantida a privacidade e a confidencialidade dos dados
4. Está garantido o uso responsável e racional dos recursos para investigação.

C – Conclusões

1. A CES reconhece a este estudo originalidade, relevância e pertinência dos resultados.
2. Face ao exposto, a CES delibera dar parecer favorável à autorização deste estudo.
3. Não obstante, deve ser obtida a autorização dos Diretores Executivos dos ACES

Aprovado na reunião de 6 de março de 2018, por unanimidade.

O relator,

Dra. Maria Deolinda Neves

O Presidente da Comissão de Ética para a Saúde da ARS Norte IP

Professor Doutor Alberto Pinto Hespanhol

APPENDIX C

Ethical committee approval – ACES

PROJECTO DE INVESTIGAÇÃO/ESTUDOS

Identificação do (s) investigador (es) do estudo

Nome Completo: Célia Margarida Viegas Domingos

Contacto telefónico: 967562248

E.Mail: id6512@alunos.uminho.pt

Qualificação Académica: Mestre em Biotecnologia

Funções que desempenha: Aluna de doutoramento em Ciências da Saúde Aplicadas
Instituição: Instituto de Ciências da Vida e da Saúde, Escola de Medicina, Universidade do Minho.

Designação do Estudo: "Caracterização de um sistema de monitorização de atividade física como substituto da estrutura e função do cérebro em idosos."

Área científica em que se enquadra o estudo: Ciências da Saúde

Vigência do Estudo (Data de princípio e de fim): Fevereiro de 2018 a Agosto de 2020

Tipo de análise (quantitativa, qualitativa): Análise quantitativa e qualitativa.

Palavras – chave: idosos; dispositivo de monitorização; usabilidade; atividade física; saúde cerebral.

Co-Investigador(es) **(quando aplicável)**

Nome(s) Completo(s):

OUTROS PROFISSIONAIS ENVOLVIDOS

(Exemplo: Orientador)

Nome(s) Completo(s): Nadine Correia Santos, PhD e José Miguel Pêgo, MD, PhD
Instituição: Instituto de Ciências da Vida e da Saúde, Escola de Medicina, Universidade do Minho.

OUTRAS INFORMAÇÕES SOBRE ESTUDO

Objetivo Geral: O objetivo geral deste projeto consiste na caracterização de um sistema de monitorização da atividade física em idosos avaliando a usabilidade, viabilidade e desempenho do sistema e a posterior correlação entre padrões de atividade física e estrutura e função do cérebro, com recurso a estudos de neuroimagem.

Metodologia:

Neste projeto, primeiramente iremos realizar um estudo observacional transversal em idosos para: (i) testar a usabilidade, viabilidade e desempenho de um sistema de monitorização da AF; (ii) explorar associações entre AF e a estrutura e função cerebral. Este estudo inicial será efetuado com recurso a questionários de AF, questionários de usabilidade e aceitação da tecnologia, recolha de dados provenientes do dispositivo e aquisições de ressonância magnética.

Por último, será efetuada uma intervenção para avaliar se o uso do dispositivo com feedback telefónico contribui para a adoção de um estilo de vida mais ativo. A intervenção terá a duração de 6 meses em que o participante deverá fazer uso do sistema de monitorização.

Critérios de inclusão

a) homens e mulheres com 65-75 anos de idade; b) capacidade de participar nas sessões de avaliação; c) capacidade de entender o consentimento informado; d) capacidades motoras visuais, auditivas adequadas ao protocolo de estudo (ex: capacidade de caminhar em segurança sem assistência, sem problemas ortopédicos, capacidade de interagir com o dispositivo, capacidade de receber o feedback por telefone).

Método de recolha dados (anexar instrumento recolha)

a) Questionário sociodemográfico;

b) Questionário de avaliação clínica;

c) Questionário de avaliação antropométrica

d) Questionários de avaliação neuropsicológica

e) Questionários de avaliação da habilidade funcional

f) Questionários de avaliação da atividade física;

g) Questionários de avaliação da qualidade de vida;

h) Questionários de avaliação da usabilidade e aceitação do dispositivo de monitorização.

Descrição do que consiste a colaboração do ACeS:

O Agrupamento de Centros de Saúde do Cávado I – Braga servirá apenas como centro de referenciação. Este processo será adaptado às condições, bem como a preferência dos respetivos Centros de Saúde.

Termo de Responsabilidade

Declaro assumir a liderança científica do projecto / estudo e as responsabilidades decorrentes da sua boa execução, bem como a do estudo em causa e suas conclusões ao ACeS Cavado I – Braga.

Data:
Assinatura:

PARECER DA UNIDADE FUNCIONAL (Quando Aplicável)

Favorável ☐ **Não Favorável** ☐

Data:
Assinaturas:

PARECER CONSELHO CLÍNICO E DE SAÚDE

Favorável ☒ **Não Favorável** ☐

Data: 10/01/2017
Assinaturas:

ACES Cávado I - Braga
Presidente do Conselho
Clínico e de Saúde
Dra. Margarida Lim...

DIRETOR EXECUTIVO

Nada a opor á sua realização,

Cristina Ferreira
Directora Executiva

AGRUPAMENTO DE CENTROS DE SAÚDE DO CÁVADO I - BRAGA
Largo Paulo Orósio
4700-036 Braga
Tel. 253 209 200
Fax 253 209 281
acesbraga@acesbraga.min-saude.pt

APPENDIX D

Ethical committee approval – Hospital de Braga

Hospital Braga

Comissão de Ética para a Saúde

Data: 29-03-2018

Refª 28/2018

Relator: Juan R Garcia

Parecer emitido em reunião ordinária de 27 de março 2018

Nos termos dos Nº 1 e 6 do Artigo 16º da Lei Nº 21/2014, de 16 de Abril, a Comissão de Ética para a Saúde do Hospital de Braga (CESHB), emite o seguinte parecer relativo ao estudo "***Caracterização de um sistema de monitorização de atividade física, como substituto da estrutura e função do cérebro em idosos***", de que é investigador principal Célia Margarida Viegas Domingos, aluna de doutoramento do Instituto de Ciências da Vida e da Saúde ICVS, e orientadores os Doutores Nadine Correia Santos, e José Miguel Pêgo, promovido pela iCognitus4ALL-IT solutions, Lda.; que decorrerá instalações do 2CA-Braga da Instituição.

O objetivo geral deste projeto consiste na caracterização de um sistema de monitorização da atividade física em idosos, avaliando a usabilidade e desempenho deste sistema e a correlação entre padrões de atividade física e estrutura e função do cérebro. Está dividido em 3 objetivos específicos: 1. Avaliar o sistema de monitorização de atividade física quanto à usabilidade e viabilidade; 2. Correlacionar a atividade física com a estrutura e função cerebral em idosos; 3. Avaliar se o feedback mediado por telefone, pode modificar o padrão de uso do sistema monitor, e o comportamento relativamente às atividades físicas diárias.

Trata-se de um estudo observacional transversal para primeiro e segundo objetivos. O terceiro será longitudinal com um desenho experimental pré-pós intervenção. O protocolo inclui os critérios de inclusão: homens e mulheres com 65-75 anos; capacidade de consentimento informado; capacidades motoras visuais, auditivas adequadas ao protocolo de estudo. E os critérios de exclusão: doença neurológica ou psiquiátrica; história de traumatismo craniano; contraindicação para ressonância magnética.

O recrutamento dos participantes será feito mediante contato prévio da equipa de investigação, bem junto do médico de família das respetivas Unidades de Saúde Familiar, bem junto das instituições (lares, centros de dia, ginásios e Universidades sénior). Será uma amostra por conveniência até 120 participantes, número aparentemente adequado para os objetivos propostos. É recolhido o consentimento expresso do participante.

Os dados a recolher consistem em: avaliação neura psicológica, e questionários sociodemográficos, antropométrico e de avaliação clínica; avaliação habilidade funcional, escala de Atividades de Vida Diárias, testes de força dos membros, avaliação da atividade física, avaliação da usabilidade e aceitação do dispositivo. Dados resultantes da monitorização de atividade física e ainda da Ressonância Magnética Estrutural e Funcional do cérebro.
O cronograma prevê finalizar os trabalhos em agosto de 2020.

A informação é recolhida diretamente do titular e indiretamente do processo clínico. De modo a garantir a confidencialidade será atribuído um número de identificação que estará apenas associado ao nome do individuo, num documento cujo acesso será restrito ao supervisor do investigador. A análise dos resultados será efetuada com recurso ao software IBM SPSS Statistics 23.0, verificando as correlações entre atividade física e a função e estrutura do cérebro (regressão linear e correlações) e avaliar as diferenças de comportamento pré- e pós a intervenção através de Ttestes ou teste de Wilcoxon e ANOVA ou teste de Friedman (para mais de dois grupos).

Os custos do projeto serão cobertos pelo responsável pelo estudo (Escola de Medicina/ICVS). Não estão previsto abuso de recursos institucionais, hospitalares e/ou outros. Não haverá lugar a despesas para os participantes nem qualquer ressarcimento ou remuneração, sendo que despesas de deslocação e alimentação, se necessário, serão cobertas pelo projeto.

Não se declaram situações de conflito de interesses por parte do investigador no estudo clínico; O Centro de Ensaio reúne todas as condições necessárias para a realização do estudo mencionado, de forma a cumprir os requisitos do protocolo clínico, normas de Boas Práticas Clinicas e Legislação aplicável, no que diz respeito a infraestruturas e equipamento.

Acerca do efeito benéfico da atividade física para as funções cerebrais, o estudo é pertinente, é acrescenta à bibliografia atual a inclusão de participantes em diferentes cenários (idosos na comunidade e institucionalizados), o que permitirá incluir indivíduos frequentemente excluídos. Além disso, diferentemente de estudos anteriores, permitirá a monitorização objetiva e contínua da atividade física diária; e será utilizada uma abordagem de neuro imagem multimodal.

São anexados os seguintes documentos:

Requerimento à Comissão Executiva do HB

Formulário da CESHB

Protocolo de investigação

CV do investigador principal e dos orientadores;

Autorização n.º 11286/ 2017 da Comissão Nacional de Proteção de Dados.

Declaração dos Presidentes de 2CA-Braga e do ICVS

Declarações de Confidencialidade e Modelo de consentimento informado - ARS.

A CESHB analisou o estudo em questão tendo achado estarem reunidas todas as caraterísticas éticas e científicas para as boas práticas da investigação clínica, e deu a sua aprovação.

O Presidente da CESHB

(Dr. Juan R Garcia)

DECLARAÇÃO

O Centro Clínico Académico – Braga, Associação (2CA-Braga), declara, para os devidos efeitos, que a estudante de doutoramento Célia Margarida Viegas Domingos irá desenvolver o estudo clínico "*Characterization of a wearable monitoring system of physical activity as a surrogate of brain structure and function in older populations*", sob a orientação da Doutora Nadine Santos; Investigadora Auxiliar do Instituto de Investigação em Ciências da Vida e Saúde (ICVS), e o Doutor José Miguel Pêgo, Professor Auxiliar da Escola de Medicina da Universidade do Minho (EMUM).

Neste contexto, na qualidade de Presidente da Direção do 2CA-Braga, venho por este meio autorizar a realização do acima mencionado estudo clinico, nas instalações do 2CA-Braga.

Declaro, ainda, que o Centro de Ensaio reúne todas as condições necessárias para a realização do estudo mencionado, de forma a cumprir na os requisitos do protocolo clínico, normas de Boas Práticas Clinicas (BPC) e Legislação aplicável, no que diz respeito a infra-estruturas e equipamento.

Braga, 18 de outubro de 2017

Presidente da Direção do 2CA-Braga

(Professor Doutor Nuno Sousa)

Centro Clínico Académico – Braga, Associação (2CA-Braga)
Hospital de Braga
Lugar de Sete Fontes – S. Victor
4710-243 Braga, Portugal

APPENDIX E

CNPD approval

Autorização n.º 11286/ 2017

iCognitus4ALL - IT Solutions, Lda , NIPC 510822304, notificou à Comissão Nacional de Protecção de Dados (CNPD) um tratamento de dados pessoais com a finalidade de realizar um Estudo Clínico com Intervenção, denominado Caracterização de um sistema de monitorização de atividade física como substituto da estrutura e função do cérebro em idosos. .

Existe justificação específica para o tratamento de dados comportamentais, psicológicos ou volitivos, os quais estão diretamente relacionados com a investigação.

O participante é identificado por um código especificamente criado para este estudo, constituído de modo a não permitir a imediata identificação do titular dos dados; designadamente, não são utilizados códigos que coincidam com os números de identificação, iniciais do nome, data de nascimento, número de telefone, ou resultem de uma composição simples desse tipo de dados. A chave da codificação só é conhecida do(s) investigador(es).

É recolhido o consentimento expresso do participante ou do seu representante legal.

A informação é recolhida diretamente do titular e indiretamente do processo clínico.

As eventuais transmissões de informação são efetuadas por referência ao código do participante, sendo, nessa medida, anónimas para o destinatário.

A CNPD já se pronunciou na Deliberação n.º 1704/2015 sobre o enquadramento legal, os fundamentos de legitimidade, os princípios aplicáveis para o correto cumprimento da Lei n.º 67/98, de 26 de outubro, alterada pela Lei n.º 103/2015, de 24 de agosto, doravante LPD, bem como sobre as condições e limites aplicáveis ao tratamento de dados efetuados para a finalidade de investigação clínica.

No caso em apreço, o tratamento objeto da notificação enquadra-se no âmbito daquela deliberação e o responsável declara expressamente que cumpre os limites e condições aplicáveis por força da LPD e da Lei n.º 21/2014, de 16 de abril, alterada pela Lei n.º 73/2015, de 27 de junho – Lei da Investigação Clínica –, explicitados na Deliberação n.º 1704/2015.

O fundamento de legitimidade é o consentimento do titular.

A informação tratada é recolhida de forma lícita, para finalidade determinada, explícita e legitima e não é excessiva – cf. alíneas a), b) e c) do n.º 1 do artigo 5.º da LPD.

Assim, nos termos das disposições conjugadas do n.º 2 do artigo 7.º, da alínea a) do n.º 1 do artigo 28.º e do artigo 30.º da LPD, bem como do n.º 3 do artigo 1.º e do n.º 9 do artigo 16.º ambos da Lei de Investigação Clínica, com as condições e limites explicitados na Deliberação da CNPD n.º 1704/2015, que aqui se dão por reproduzidos, autoriza-se o presente tratamento de dados pessoais nos seguintes termos:

Responsável – iCognitus4ALL - IT Solutions, Lda

Finalidade – Estudo Clínico com Intervenção, denominado Caracterização de um sistema de monitorização de atividade física como substituto da estrutura e função do cérebro em idosos.

Categoria de dados pessoais tratados – Código do participante; idade/data de nascimento; género; dados antropométricos; sinais vitais; composição do agregado familiar sem identificação dos membros; dados da história clínica; dados dados de exame físico; dados de meios complementares de diagnóstico; medicação prévia concomitante; dados de qualidade de vida/efeitos psicológicos; comportamentais, psicológicos ou volitivos com conexão com a Investigação

Exercício do direito de acesso – Através dos investigadores, por escrito

Comunicações, interconexões e fluxos transfronteiriços de dados pessoais identificáveis no destinatário – Não existem

Prazo máximo de conservação dos dados – A chave que produziu o código que permite a identificação indireta do titular dos dados deve ser eliminada 5 anos após o fim do estudo.

Da LPD e da Lei de Investigação Clínica, nos termos e condições fixados na presente Autorização e desenvolvidos na Deliberação da CNPD n.º 1704/2015, resultam obrigações que o responsável tem de cumprir. Destas deve dar conhecimento a todos os que intervenham no tratamento de dados pessoais.

Lisboa, 09-10-2017

A Presidente

Filipa Calvão