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Crowley, Patrick Joseph

DOI (link to publication from Publisher):
10.5278/VBN.PHD.MED.00131

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

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BY
PATRICK JOSEPH CROWLEY

DISSERTATION SUBMITTED 2021

AALBORG UNIVERSITY
DENMARK

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Dissertation submitted

Dissertation submitted: 29-01-2021

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ISSN (online): 2246-1302
ISBN (online): 978-87-7210-887-2

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2021

CV

Patrick Crowley graduated from the School of Physiotherapy & Performance Science, University College Dublin (UCD), Ireland, in 2014 with a BSc. in Health and Performance Science. Three years later, in 2017, he graduated with a MSc. in Sports Technology from the Faculty for Health Science and Technology, Aalborg University (AAU), Aalborg, Denmark. During this masters degree Patrick Crowley completed a research stay at the laboratory for Autonomie Gérontologie, E-santé, Imagerie & Société, at the Université Grenoble Alpes (UGA), Grenoble, France, under the supervision of Dr. Assoc. Prof. Nicolas Vuillerme.

In 2018, Patrick Crowley was employed at the National Research Centre for the Working Environment (NFA) Copenhagen, Denmark, on a 3-year contract funded by the Danish Work Environment Fund (AMFF). Later that year, he was enrolled as a Ph.D. student under the Co-Totutelle agreement, between the Doctoral School for Biomedical Medicine of AAU and the École Doctorale Ingénierie pour la Santé, la Cognition et l'Environnement at UGA. Supported by the Department for Musculoskeletal Disorders and Physical Workload (MSB group) at NFA.

Patrick Crowley has given two oral presentations at the International Conference on Ambulatory Monitoring of Physical Activity and Movement (ICAMPAM) and two further presentations for the Partnership for European Research in Occupational Safety and Health (PEROSH). He has also contributed considerably to the AMFF-funded *Age and Recovery* project, in collaboration with Dr. Matthew Stevens and Prof. Andreas Holtermann at NFA, investigating whether older workers have a greater need for recovery than their younger colleagues do. He conducted a proof-of-concept study on behalf of the international Prospective Physical Activity, Sedentary behavior, and Sleep Consortium (ProPASS).

ENGLISH SUMMARY

Walking serves as an important source of information for the research of human movement and behavior. In fact, the observation of walking adaptation, in response to the surrounding environment, can reveal a great deal about our everyday activity, functioning and health. Although traditionally, the observation of walking – or gait - is primarily performed in a laboratory, the findings of Study I highlighted the need for more ecologically valid protocols and analysis, not in gait laboratories. Therefore, this dissertation presents the measurement of gait in more ecologically valid settings using non-obstructive body-worn sensors, while incorporating three different constructs or paradigms. 1) Gait-quality - the measurement of *how* we walk. 2) Gait-quantity – the measurement of how *much* we walk. 3) The Dual Task paradigm – the measurement of cognitive and physical performance under conditions of multitasking, as compared to performance under single task conditions. Accordingly, the protocol for investigating the dual task effect on gait-quality was designed to reflect the everyday "dual task" setting (Study II-III). This was achieved by asking participants to walk over ground, as opposed to a treadmill, at a self-selected walking speed with minimal instruction regarding task completion (Study II-III), and further, through the selection of a secondary task that replicated an everyday dual task: mobile phone use while walking. Further consideration was given to ecological validity in the cross-sectional analysis of gait-quantity in the daily work setting of white- and blue-collar workers (Study IV). Gait-quantity, defined as the number of steps and the cadence at which the steps occurred, was divided according to work and leisure hours - hereafter referred to as work and leisure *domains*. This division more accurately reflected everyday behaviors. In addition, the domain of steps was suspected to have implications for the associations between walking and health. Gait-quality assessed using spatiotemporal stride parameters indicated significant changes in how young adults walked when using a mobile phone (Study II). Walking speed, stride length and cadence all decreased while double support time increased. In addition, there was a clear increase in the relative variability of these parameters when using a mobile phone. Further assessment using the nonlinear analysis of trunk acceleration patterns, indicated that both walking speed instruction and the use of a mobile phone significantly affected walking (Study III). The analysis of gait-quantity highlighted the importance of domain information on the quantity of walking in white- and blue-collar workers, and its associations with health (Study IV). When observed in more ecologically valid settings, the effect of mobile phone use on gait-quality appeared small, amongst young adults, while including domain information in the analysis of gait it was important for the quantity and association with health. In conclusion, future research should strongly consider the ecological validity when measuring these constructs and paradigms of human walking.

DANSK RESUME

Måden, vi går på, er en vigtig informationskilde i forskningen i menneskers bevægelse og adfærd. Faktisk kan observation af, hvordan man tilpasser sin måde at gå på i forhold til det omgivende miljø, fortælle meget om vores daglige aktivitet, funktion og helbred. Traditionelt set har man primært observeret vores måde at gå på – også kaldet gang – i et laboratorium, dog understregede resultaterne fra Study I behovet for en højere grad af *ecological validity* i protokoller og analysemetoder, som udføres uden for et laboratorium. Derfor præsenterer denne afhandling målinger af gang i mere *ecologically valid* omgivelser ved brug af ikke-hindrende kropsmonterede målere og med inddragelse af tre forskellige paradigmer. 1) Kvaliteten af gang – hvordan vi går. 2) Kvantiteten af gang – hvor meget vi går. 3) *Dual-Task paradigmet* – hvordan vi præsterer både fysisk og kognitivt, når vi skal multitaske sammenlignet med, hvordan vi præsterer, når vi ikke skal multitaske. Af denne grund blev protokollen, der skulle undersøge *dual-task* effekten på gang-kvalitet, designet, så den afspejlede dagligdagssituationer, hvor *dual-tasks* opstår (Study II og III). Dette blev opnået ved at bede deltagerne om at gå henover jorden, i stedet for på et løbebånd, i selvvalgt hastighed med minimal instruks om, hvordan de skulle udføre opgaven (Study II & III). Derudover blev der valgt en anden opgave, som efterprøvede en dagligdags *dual-task*: brugen af mobiltelefon mens man går. *Ecological validity* blev taget yderligere i betragtning i tværsnitsanalysen af gang-kvalitet i *white-collar* og *blue-collar* medarbejderes daglige arbejdsomgivelser (Study IV). Her blev gang-kvantitet defineret som antal skridt og den kadence, de forekom i, delt op i skridt på arbejde og skridt i fritiden – herefter refereret til som domæner. Denne opdeling afspejlede på mere korrekt vis dagligdagsadfærd. Derudover var der en formodning om, at skridt-domænet kunne have betydning for forventede sundhedssammenhænge. Gang-kvalitet, der vurderes ved hjælp af skridtparametre, indikerede signifikante ændringer i, hvordan unge voksne gik, mens de brugte en mobiltelefon (Study II). Ganghastighed, skridtlængde og kadence blev alle reduceret, samtidig med at double-support time steg. Derudover var der en tydelig stigning i variabiliteten af disse parametre, mens deltagerne brugte en mobiltelefon. Nærmere undersøgelser med brug af non-lineære analysemetoder af torso-accelerationsmønstre indikerede, at både instruktion om ganghastighed og brugen af mobiltelefon havde betydelig indvirkning på gangen (Study III). Analysen af gang-kvantitet understredede vigtigheden af domæneinformation både for kvantiteten af skridt blandt *white-collar* og *blue-collar* medarbejdere og sammenhængen mellem gang og sundhed (Study IV). Når deltagerne

blev observeret i mere *ecologically valid* omgivelser, virkede effekten af mobilbrug på gang-kvaliteten lille blandt unge voksne. Samtidig virkede det vigtigt at inkludere domæneinformation i analysen af gang-kvantitet både for kvantiteten og sundhedssammenhænge. Afslutningsvis bør fremtidig forskning i høj grad overveje *ecological validity*, når disse konstruktioner og paradigmer måles.

ACKNOWLEDGEMENTS

The current dissertation was made possible through the support of; the National Research Centre for the Working Environment, Copenhagen; the Department of Health Science and Technology at Aalborg University; and the Université Grenoble-Alpes. I would like to thank my supervisors for their support throughout the project. Pascal Madeleine for guiding and mentoring through first my master's degree, and now this PhD dissertation - your valued advice and support has always been exactly what I needed, exactly when I needed it. Nicolas Vuillerme for inspiring the project and encouraging the work and effort throughout – you taught me to think critically and to take the initiative; attributes I hope to carry with me throughout my career. Andreas Holtermann for providing the energy from day-to-day, the guidance and the discussion - your passion and enthusiasm is infectious, in the best possible way.

Thank you also to my co-authors Afshin Samani and Nidhi Gupta. Afshin for your attention to detail, explanations and patience. Nidhi for guiding me through new analysis techniques and reassurance along the way.

Thank you to the MSB research group at NFA for the support and fællesskab over the past few years. Directly or indirectly, you have been a big help. Anne Cathrine Tjellesen, research boss at the MSB group, for your consistent support even when things did not got exactly to plan or as promised.

Finally, to my Irish and Danish families for the frequent check-ins, support and grammar lessons.

- Patrick

January 2021, Copenhagen.

FOREWORD

“As rich as it is in variety, walking does not compete in status and attention as movements of the hand or the mouth. Inseparable from the foot and earth it threads, walking is taken to be mundane, ordinary, pedestrian, and even besmirched and polluted – and thus in all ways worthy of being overlooked or disdained” … Forever “camouflaged in context”

-Amato JA,
On foot: A History of Walking, New York University Press 2004.

The quote from Amato captures succinctly how walking is often overlooked as just another unremarkable part of the everyday. It is rarely at the forefront of our minds because most people can effortlessly adapt their gait in response to internal and external environmental cues, adapting to context. It is through this seamless adaptability that variations in walking become camouflaged, and it is precisely because of this ability to adapt, that walking is such a rich source of information for understanding human behavior and health.

Study I: Crowley, P., Madeleine, P., & Vuillerme, N. Effects of mobile phone use during walking: A review. *Critical Reviews in Physical Rehabilitation* Medicine, 28(1-2):101-119 (2016).
Study II: Crowley, P. Madeleine, P., & Vuillerme, N. The effects of mobile phone use on walking: a dual task study. *BMC Research Notes*, 12:352 (2019).
Study III: Crowley, P., Vuillerme, N., Samani, A., & Madeleine, P. The effects of walking speed and mobile phone use on the walking dynamics of young adults. *Scientific Reports*. 11(1), 1237 (2021).
Study IV: Crowley, P., Gupta, N., Vuillerme, N., & Madeleine, P., Holtermann, A. Step quantity and systolic blood pressure: do domain and job type matter? *Submitted.*

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

Walking is a learned activity necessary for a wide range of human behaviors. For most, walking is fundamental for daily duties, also contributing to the daily dose of physical activity and hugely beneficial to health. We develop how we walk, our gait, in our own idiosyncratic way, reflecting everything from our job and social status, to our environmental surroundings and health. In the following dissertation, four original research studies will highlight how gait can give us insight into behavior and health. In particular, the potential of interpreting information on *how* we walk and *how much* we walk in relation to behavior and health, when measured in an ecologically valid setting.

In this introduction, the constructs and definitions of gait-quality and gait-quantity – the *how* and *how much* - will be introduced (fig 1-1), as will the Dual Task paradigm and other implemented methods and theories used throughout the studies compiled in this document. The dissertation was completed at Aalborg University (Denmark) in collaboration with the Université Grenoble Alpes (France) under the Co-tutelle agreement and the National Research Centre for the Working Environment Copenhagen (Denmark).

1.1. GAIT-QUALITY AND QUANTITY

Gait-quality and gait-quantity can be defined using a range of measures. For example, measures of regularity, smoothness, variability and consistency to define gait-quality and measures of bouts, durations, and absolute value to define gait-quantity (1-4). In this dissertation, gait-quality is defined by spatiotemporal stride parameters; including gait speed, stride length, cadence, and double support time, as well as, the regularity, variability, and local dynamic stability (Study II & III). While gait-quantity is defined as the number of steps per day, at work and at leisure (Study IV), as well as the duration these steps occur at a cadence of above and below 100 steps per minute (Fig. 1-1). These gait constructs are an important source of information that provide insight into numerous aspects of behavior and function, including the effects of aging, pathology, physical activity, and general health (4-13). In the subsequent chapters, it will be demonstrated how the measurement of gait-quality can be used to delineate changes in walking under conditions of a varying degree of cognitive and physical load, while also presenting a novel analysis of gait-quantity to explore the association between gait and health, incorporating information on domain (i.e. work and leisure hours) and job type (blue-collar and white-collar).

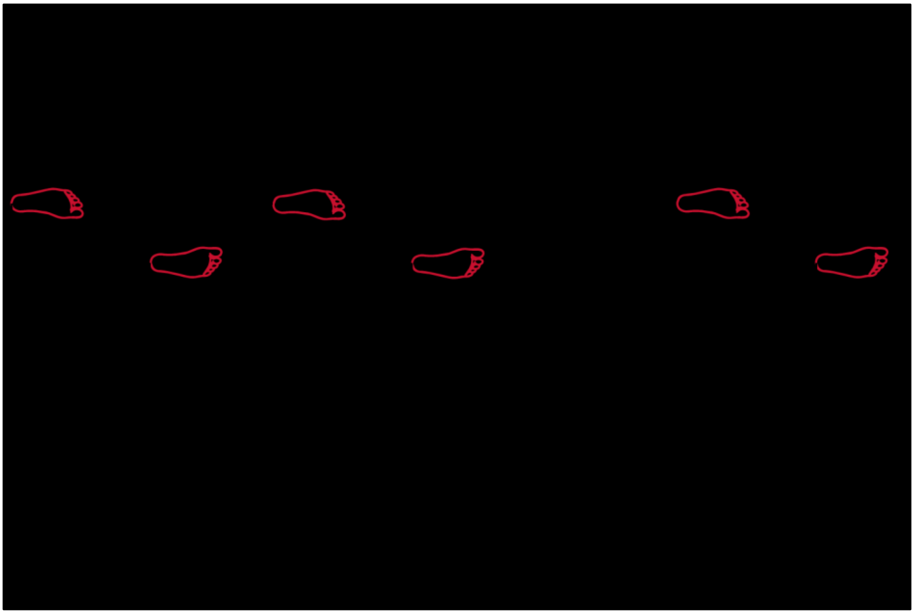

Figure 1-1. The constructs of gait-quality and gait-quantity. In the current dissertation, gait-quality is assessed using spatiotemporal stride parameters (Study II) and the variability, regularity and local dynamic stability (Study III). Gait-quantity is assessed using the number of steps (Study IV). (Figure adapted from Study I)

1.2. THE DUAL TASK PARADIGM

The dual task paradigm provides a construct for assessing altered performance in the primary and secondary tasks individually, as well as in the performance of both tasks simultaneously (14) (figure 1-3). This methodology has been applied widely in gait research (15) partly because of the high demand placed by gait on cognitive resources (16, 17), but mostly, because of the benefits to a wide range of clinical conditions including Parkinson's disease (18), post stroke rehabilitation (19), and fall prone adults (20, 21). The dual task paradigm is also frequently implemented among healthy participants to explore cognitive control processes (22, 23). In particular, mobile phones are now frequently used as the secondary task (24), providing a highly relevant, everyday, example of the dual task paradigm one that is particularly prevalent among young adults (25).

Figure 1-2. The dual task paradigm with dual task cost presented as the percentage change in performance. It is also valid to present dual task cost in absolute values.

1.3. GAIT MEASUREMENT USING TRIAXIAL ACCELEROMETERS

The development of small, wireless, lightweight sensors containing tri-axial accelerometers has opened up the possibility of measuring gait without the limitations of a laboratory and at a relatively low cost in comparison to traditional methods (26) e.g. motion capture (27). Accelerometry, defined as the use of accelerometers to measure human movement (26), allows factors such as the walking surface (28), level of distraction in the surrounding environment (29), the walking instruction provided (30), and domain of activity (31) to be incorporated into the protocol design. The following section will provide some background and rationale for the different accelerometer placements used (Studies II-IV), as well as the strengths, weaknesses and considerations associated with these devices.

1.3.1. SHOE-WORN ACCELEROMETER

Shoe-worn sensors are often preferred for clinical gait analysis and assessment because they provide the most accurate detection of initial and end foot contact, thus enabling the precise detection of a gait cycle (32). This gait cycle can then be divided into its sub-components providing the information necessary for analysis of multiple spatiotemporal stride parameters (33, 34) including gait velocity, stride length, cadence, and double support time (Study II). Additionally, gait parameters specific to each limb can be detected, facilitating the assessment of gait asymmetry (35).

1.3.2. TRUNK-WORN ACCELEROMETER

Trunk-worn sensors have the advantage of requiring just a single sensor and can be placed at a central position that largely reflects the movements of the lower limbs and those of the head and trunk simultaneously (36-38). Essentially the movements of the head and limbs are transmitted through the trunk. This makes this placement extremely useful when looking at gait as a system (Study III).

1.3.3. THIGH-WORN ACCELEROMETER

Similar to trunk-worn sensors, thigh-worn accelerometry exploit a particular body position. Using just a thigh accelerometer it is possible to classify not only parameters of gait-quantity, but also physical activity and posture types (39). This large classification potential has lead to increasing popularity in large scale public health research (40-43), making it a highly relevant placement for further research and the measurement of gait-quantity (Study IV).

1.3.4. WRIST-WORN & HIP-WORN ACCELEROMETER

Wrist and hip worn accelerometers are also frequently used to measure physical activity (44), energy expenditure (45) and step count (46). These placements gained popularity owing to an increasing interest in how to improve the wear compliance in studies aiming to collect data over multiple days (47). Due to its convenience, the wrist is perhaps the most attractive placement, particularly among young adults (48, 49). The proliferation of commercial wrist-worn sensors may be reflective of this (45, 50). However, the wrist-worn accelerometer although easy to wear is still susceptible to misplacement (51). Moreover, in terms of step counting, a wrist-worn accelerometer appears to overestimate the number of steps, in comparison with the more central hip placement on the body (46).

1.3.5. FURTHER CONSIDERATIONS FOR ACCELEROMETER PLACEMENT

There will always be debate about which accelerometer placement is "best", because particularly for large epidemiological cohorts, the decision ultimately depends on the research question at hand; in the definition of the methodology and the construct of the physical activity that is considered important (52-54). A clear benefit of the thigh-worn accelerometer is its capacity to classify physical activity, posture types, and sedentary behavior (39, 55). Yet, large cohorts also chose to use wrist and hip worn sensors (56, 57). Ultimately, no one accelerometer placement or protocol will be sufficient for all research questions, as the data requirements can range from detecting the prevalence of a specific physical activity, posture or movement to detecting the habitual occurrence of physical activity and energy expenditure, justifying compromise in terms of methods of analysis (58).

1.4. THEORIES OF MOVEMENT, GAIT & HEALTH

The interpretation of human movement has evolved considerably over the past few decades, moving from traditional to more contemporary conceptualizations and theories developing along with the understanding of the field, with gait, as an area of study, naturally subject to this change. The link between gait and health has in fact been suspected for quite some time, as illustrated by a London letter to the Journal of American Medical Association in 1909 calling attention to "a form of exercise [walking] as healthful as, in this country it is uncommon" (59). Since then research has slowly built up supportive evidence for this (60). This section will introduce an interpretation of variability in human movement and an applied theoretical framework, as well as, a brief consideration of how gait, accelerometry and health are related.

1.4.1. VARIABILITY IN MOVEMENT

The traditional conceptualization of variability as a sign of dysfunction in movement has developed to an interpretation whereby variability is viewed along a spectrum – indicating that variability is actually required for functional movement (61-63). This has important implications for the analysis of gait, because traditional methods rely on statistics concerned with centrality, such as the mean, standard deviation from the mean and coefficient of variation. It is difficult to quantify accurately how much variability is "good" or "bad", using these statistical methods alone, because the degree of movement variability changes over time and will, therefore, be obscured by these averages (64). In other words, variability fluctuates. Therefore, if only the average of this fluctuation is considered, important information regarding the change in fluctuation over time is lost. Thus, traditional methods are fundamentally limited by their inability to track variability in movement as it is related to time. Study III addresses this issue using novel methods and a trunk-worn accelerometer.

1.4.2. DYNAMICAL SYSTEMS THEORY

In place of these measures of central tendency, Dynamical Systems Theory provides a framework and tools for the exploration of the changes in movement variability over time (66). A dynamic system is one that changes over time, and since walking is essentially the manifestation of multiple mechanisms interacting and changing over time, one could, and perhaps should, consider human walking as a highly complex dynamic system (67, 68). It is argued that the variability of such a system over time, is likely to hold important information (66). However, there is still much debate and the calibration of these methods is far from simple. Firstly, it is extremely difficult to establish a "ground-truth" for complexity and regardless, a full analysis of complexity is likely to require analysis of sub-mechanisms within the system, across multiple time scales (Study III). Therefore, there is no singular "ground truth" of complexity to reference. Furthermore, the intricacies of the methods make them difficult to use, especially as small changes in methodology can lead to very different results. This has led to a difficulty in applying these methods in clinical or practical settings. However, some research has been successful in applying particular nonlinear analyses to different populations; reporting links with pathology (6), local gait stability (69), and aging (70). Study III demonstrates how these methods can be applied to dual task and gait.

1.4.3. GAIT AND HEALTH

The association between walking and health have been investigated for quite some time (60, 71). Gait research was initially confined to the clinical setting, and carried out in laboratories specifically designed for gait measurement and consisting of three main observation methods: visual observation, quantitative measurement and biomechanical analysis (72). Gait was largely treated as a tool to determine the presence of certain illnesses, health and functionality (73). The development of new measurement techniques and technology has allowed the observation of gait to move away from these constraints (26, 73). In particular, accelerometry, the measurement of movement using accelerometers (26), has opened up new clinical applications and possibilities while improving the evidence base that links gait to health (26). Similarly, accelerometry has opened up new possibilities in public and occupational health research (41, 74). In this context, gait-quantity is primarily reported as an accessible measure of daily physical activity (e.g. daily steps) (60) and frequently implemented in health interventions since the arrival of the pedometer (75), with good reason, as strong evidence links a higher daily step quantity with reduced mortality rate (76), blood pressure (77), diabetes progression (78) and markers of cardiovascular risk (13). Step quantity can further be supplemented with intensity estimates, through the calculation of stepping cadence (79). An application of a thigh-worn accelerometer for the measurement of gait-quantity is presented in Study IV.

1.5. ECOLOGICAL VALIDITY

There is little consensus on a definition of ecological validity but this is perhaps unsurprising as this umbrella term will depend on the nature of the specific research, including the setting, context, and nature of the particular task, behavior and response (80). Some have argued that ecological validity can be addressed from two different approaches: verisimilitude or veridicality (81). These approaches can be defined as the degree to which the test resembles the everyday environment under investigation and the degree to which existing tests are empirically related to the everyday (81). Each approach has limitations, so inevitably there will need to be a degree of compromise (81). The goal then, is to find a balance between sufficient experimental control and an experimental setting that adequately reflects the natural environmental characteristics (82).

1.6. AIMS AND HYPOTHESES

This PhD dissertation presents techniques to capture the gait-quality (Study II & III) and gait-quantity (Study IV), while interpreting their role with respect to the dual task effect, domain and health. The aim of Study I was to identify the best current practice of mobile phone dual task methodology, to identify gaps in the current knowledge base, and to report the primary spatiotemporal stride parameters relevant to this research. The aim of Study II was to implement the best current practice in an ecologically valid experimental protocol aimed at closing the identified research gap – mainly the effect of mobile phone dual task on the gait, when walking over ground and under the influence of differing walking speed instructions. The aim of Study III was to determine the effects of mobile phone dual task on walking dynamics including local dynamic stability and regularity. Finally, the aim of Study IV was to investigate the association between step quantity and systolic blood pressure, in a more ecologically valid analysis incorporating information on domain (work and leisure hours) and job type (blue-collar or white-collar) to more accurately reflect the reality of everyday among working age adults.

It was hypothesized that the influence of a mobile phone dual task would be exacerbated by walking at a fast pace and that the variability of spatiotemporal stride parameters would increase under dual task conditions (Study II). Further, on the basis of trunk accelerometry, it was hypothesized that local dynamic stability would decrease at a sub-optimal walking speed and the dual task effect of competition for attentional resources (Study III). Finally, it was hypothesized that steps at leisure would be associated with more reductions in systolic blood pressure than steps at work (Study IV). Taken together the findings of this dissertation highlight the importance of considering ecological validity when investigating gait-quality, gait-quantity, the dual task effect, domain and health.

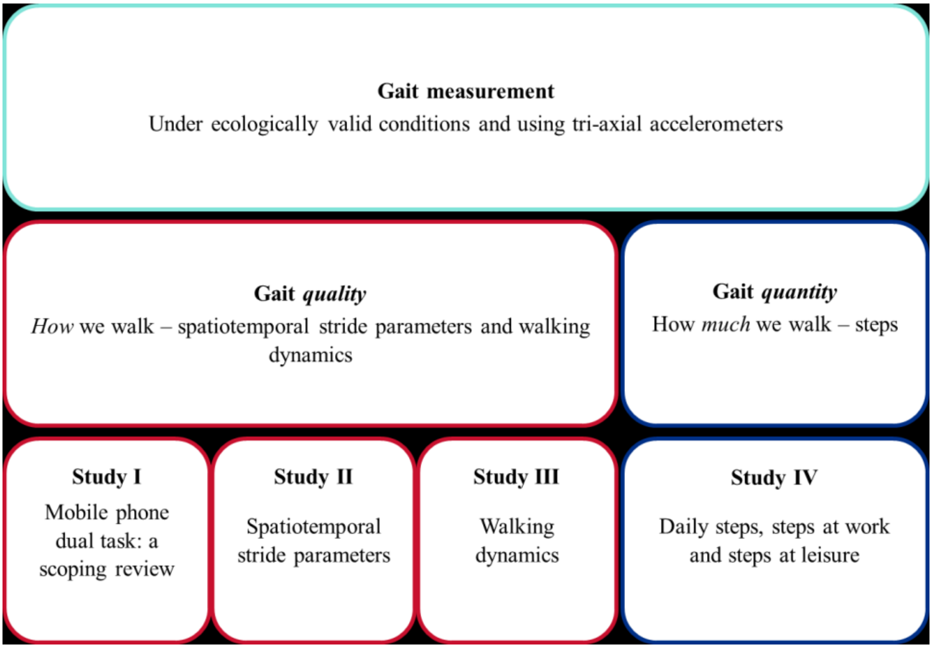

Figure 1-3. Study overview detailing the constructs of gait-quality and quantity. Studies I-III detail the investigation of gait-quality and mobile phone dual task. Study IV explores gait-quantity and the influence of the domains – work and leisure.

CHAPTER 2. METHODS

The following chapter provides an overview of the measurement and analysis methods used. Further information can be found in the appendices where Studies I - IV are listed.

2.1. RECRUITMENT

Gait-quality was investigated in Study II and III, and for this purposes 20 healthy young adults, recruited through word of mouth. A portion of this data formed part of Patrick Crowley's master thesis. Of note, additional recordings were made at a later stage. In both studies, the collected data was re-processed and analyzed, leading to new interpretations of the findings. The data used for Study IV was collected as part of DPHACTO study. A full cohort description has been published elsewhere (83). Data from 694 of these participants were included in Study IV. All participants provided written informed consent prior to participating. Studies II and III were approved by the ethics committee in the North Denmark Region – LBK number 1083. Study IV uses data collected as part of the Danish Physical Activity Cohort with Objective measurements (DPHACTO) study, approved by the Danish data protection agency and local ethics committee (H-2-2012-011).

2.2. THE MEASUREMENT OF GAIT

Study II and III used the accelerometer capacity of the Physilog inertial motion unit (Gait Up, Lausanne, Switzerland). Study IV used data from the Actigraph GT3X (Actigraph LLC, Florida, USA). Three different sensor placements were used. Over the laces of each shoe attached by an elastic Velcro strap (Study II). On lower back at the level of lumbar vertebrae L3 to L4 (Study III) and mid-way between the anterior superior iliac spine and patellar tendon, on the anterior surface of the right thigh (Study IV). Acceleration was sampled at 200 Hz for the measurement of gait-quality and at 30 Hz for the measurement of gait-quantity. The difference in sampling frequency reflects the required detail and the duration of recordings. Actigraph sensors were intended to record accelerations 24-hours per day, for 3-5 consecutive days. Too high a sampling frequency would result in unnecessarily large files and affect the accelerometer recording capacity.

2.2.1. PROTOCOL

The data presented in Study II and Study III were collected along a well-lit 80-meter indoor corridor. Participants were asked to complete 12 walking trials, consisting of six walking trials repeated once. Participants walked in the single task condition (i.e. without using a mobile phone), and in two dual task conditions, while texting on a mobile phone, and while talking on a mobile phone. Each for these conditions were performed at self-selected normal and fast walking speeds (Study II & III). Text messages were sent to the participant's phone at the beginning of each texting trial. Texting content consisted of questions covering the topics of hobbies, food, music, sport, film, and education. Participants were instructed to press 'send' once they reached the end of the corridor, regardless of whether they had finished texting or not. Text messages were analyzed for number of characters, the percentage of errors, and the characters typed per second (Study II & III).

Parameter	Unit	Gait-quality	Gait-quantity
Gait speed	meters per second	✓	
Cadence	steps per minute	✓	
Stride length	m	✓	
Double support time	% of gait cycle	✓	
Root-mean-square ratio	arbitrary unit	✓	
Sample entropy	unitless	✓	
Local dynamic stability	bits	✓	
Number of steps	steps		✓
Cadence bouts	hours		✓

Table 2-1. The parameters selected to measure gait-quality and quantity within through studies II-IV. Gait-quality was assessed in a sample of 20 young healthy adults. Gait-quantity was assessed in 694 workers, 560 of which were blue-collar job type and 134 of which were white-collar job type.

The step quantity reported in Study IV was derived using data collected from blue-collar and white-collar Danish workers, measured 24-hours per day over consecutive days. Domain information (i.e. work and leisure hours) was gathered using a diary provided to participants at the start of testing (Study IV). Job type was determined using a single item (What is your main occupation? 1 = blue-collar, 2 = white collar). Blue-collar was assumed to represent socioeconomic factors such as a short formal education, low wage and predominantly physical work tasks. White-collar represented administrative workers, and therefore represented a longer formal education, higher wage and sedentary primary job tasks. Further information on the DPHACTO cohort and data collection can be found elsewhere (83, 84).

2.2.2. OUTCOME MEASURES DERIVED USING A SHOE-WORN ACCELEROMETER

Spatiotemporal stride parameters including gait velocity, cadence, stride length, and double support time were derived from accelerations recorded using shoe-worn inertial motion units (Table 2-1). The Physilog Research Toolkit (Gait Up, Lausanne, Switzerland) was used to download and derive spatiotemporal stride parameters. The coefficient of variation (CV) for each of these spatiotemporal stride parameters was then calculated in Microsoft Excel (Microsoft Corp, Santa Rosa, California) (Study II). The mean and standard deviation of spatiotemporal stride parameters are established metrics of reference gait and subsequent gait changes that can occur (85, 86). The CV provides a metric of *relative* variability that allows for easy comparison across walking conditions (Study II).

2.2.3. OUTCOME MEASURES DERIVED USING A TRUNK-WORN ACCELEROMETER

Walking dynamics were defined as the root-mean-square ratio (RMSratio), sample entropy (SaEn), and the maximum Lyapunov exponent (MaxLyE), under these mobile phone dual task walking conditions (Study III). The RMSratio places the magnitude of acceleration along each axis – anteroposterior, vertical and mediolateral - relative to the total acceleration magnitude (i.e. the sum of accelerations in each direction (87). This formulation of results highlights proportional shifts in the magnitude of acceleration. Because this method accounts for the total acceleration, magnitude is made robust to changes in walking speed (87), allowing for comparison between walking periods at different speeds (Study III). Sample entropy estimates the rate of information production of a dynamical system (88). It provides an indication of predictability and from this the complexity of a time series can be assessed. A time series is simply data points collected over time (i.e. timestamped data). For a time series of length ‘n’-samples or data points, sample entropy assesses the number of matching vectors of length ‘m’, similar within the acceptable tolerance radius ‘r’ (88). The maximum Lyapunov exponent was calculated using the Wolf algorithm, which uses a single copy of a single orbit to map the trajectory of the whole dynamic system (89). The maximum exponent is the largest rate of divergence in system trajectories, where an increase in the exponent value indicates a greater divergence in system trajectories (90). This calculation was made on time-normalized data to account for differences in time-series length, which occurred because of different walking speeds leading to shorter or longer recordings because of the duration of time needed to walk the 80-meter corridor (i.e. fewer or more data points) (91). The calculation requires a time delay estimate, at which time-lagged copies should start and this was estimated using an average of mutual information analysis. A time-lagged copy is a copy, which starts its evolution with a slight time delay in comparison to the non-lagged original. This analysis identifies the first time delay with the least amount of mutual information is provided by neighboring data points (92). Additionally, this provides an estimate for the correct dimension in which to recreate the evolution of the dynamic system. Global False Nearest Neighbors (GFNN) analysis (92) was used to estimate this dimension. GFNN works by estimating the distance between neighboring data points and observing how this distance changes as the number of dimensions is increased. In other words, data points that are apparently neighbors in two-dimensional space may not in fact be neighbors when viewed in three-dimensional space. By sequentially increasing the dimensional resolution in this manner, it is possible to identify which data points are true nearest neighbors and at which dimension the system dynamics are fully unfolded. Using averaged time delay and embedding dimension estimates the maximum Lyapunov exponent was calculated for each walking trial.

2.2.4. CONSIDERATION FOR THE CALCULATION OF THE LYAPUNOV EXPONENT

Two algorithms are predominantly reported in the literature: the Rosenstein and the Wolf algorithms (69). The Wolf algorithm was chosen for Study III because of work indicating that it was more suitable for short experimental data sets (93). Yet, it is important to acknowledge that the Wolf algorithm also has its own limitations including a susceptibility to noise and a reliance on the selection of initial fixed parameters (89). As reported in Study III, steps were taken to reduce the impact of these limitations. A conservative low pass filter was applied to reduce the noise level and initial parameters were reported to facilitate replication (Study III). It is acknowledged that filtering before calculation will distort some of the inherent structure of variability, thus losing important information from the data (94). However, in their original paper describing the algorithm, Wolf et al. 1985 concluded that the impact of conservative filtering was unlikely to affect “the divergent nature of the attractor” (89) (Study III). More recent research has supported this suggestion, showing that although both noise and filtering will affect the derivation of the MaxLyE, low pass filtering with a high cut off frequency (i.e. 50 Hz) is likely to produce a consistent outcome (95, 96). Finally, the choice of using an average of individual embedding dimension and time delay estimates was based on the research indicating that this produces better consistency and validity when comparing between repeated measurements (97, 98).

2.2.5. OUTCOME MEASURES DERIVED USING A THIGH-WORN ACCELEROMETER

Steps were calculated using the instantaneous frequency derived through frequency analysis of thigh-worn accelerometer data (99). Acceleration along the longitudinal axis of the thigh – parallel to the femur - underwent fast Fourier transformation, using a running window of approximately 4 seconds separated by 1 second between windows (99). This instantaneous step frequency underwent integration for each identified walking, stair climbing, and running interval, classified using the Acti4 software (99). The classification of walking, stair walking and running using a thigh-worn sensor has been described previously in detail (39). Work and leisure domains were identified using diary information provided by participants (Study IV). The average step quantities were calculated according to the number of valid measurement days available. If more than two valid measurement days were available, then the average of the two measurement days with the longest measurement periods was taken. If only two valid measurement days were available, then the values of the day with the longest measurement period were taken as the average. If only one valid measurement day was available, then the values of that day were used. The criteria for a valid measurement of day is described in Study IV. In order to be considered as a representative measure of habitual physical activity, the current best practice suggest between 3-5 days (54), with an aim of 7 days if weekend and weekday measurement is desired (53). However, recent research indicates that it is the sample size, and not the number of days, that plays the important role in reducing the standard error of measurement (58). Thus, the averaging method implemented in Study IV maximizes the sample size by not excluding participants based on a required number of measurement days. Walking cadence was calculated as the time spent at a cadence above and below 100 steps per minute, a widely recognized meaningful “heuristic threshold” (79), during walking periods *only*.

2.3. ADDITIONAL OUTCOME MEASURES

2.3.1. DUAL-TASK COST

Dual-task Cost (DTC) is the change in performance with the addition of a secondary or dual task, presented as the absolute or percentage change with respect to the single task condition. As such, DTC is the absolute or relative percentage performance decrease attributable to the addition of a dual-task. This is an important consideration when investigating dual-task conditions with different sensory demands (100) (Study I). Here DTC is presented as the percentage change in performance, as in Study I.

2.3.2. RATING OF PERCEIVED EXERTION

Participants were asked to rate their perceived exertion on a 15-point Borg Scale (101) following each walking trial and each texting familiarization round to assess the changes in perceived exertion owing to the different sensory demands of the dual-task conditions (Study II).

2.3.3. TEXTING PERFORMANCE

Texting performance defined as characters-per-second was compared for under single task and dual task conditions (Figure 1-2) (Study II & III).

2.3.4. SYSTOLIC BLOOD PRESSURE

Blood pressure was measured as part of a worksite health check (102). After 10 minutes of still and quiet sitting blood pressure was measured three times using the OMRON M6 Comfort (Omron Healthcare, Kyoto, Japan). The average systolic and diastolic blood pressure in millimeters of mercury (mmHg) over the three measurements was used for analysis. As systolic and diastolic measurements showed a clear linear association (figure 2-1), only systolic blood pressure was included in the statistical analysis. Physiological outliers were considered as a diastolic blood pressure of less than 50 mmHg or greater than 130 mmHg. For systolic blood pressure, these thresholds were less than 80 mmHg and greater than 240 mmHg in line with previous research (102). Blood pressure status was determined according to the American Heart Association thresholds (Table 2-2).

Blood pressure status*	**Systolic blood pressure** (mm Hg)		**Diastolic blood pressure** (mm Hg)
Normal	<120	*And*	<80
Elevated	120-129	*And*	<80
High 1	130-139	*Or*	80-90
High 2	≥140	*Or*	≥90
Critical	>180	*And/Or*	>120

Table 2-2. Blood pressure thresholds according to the American Heart Association website (103)

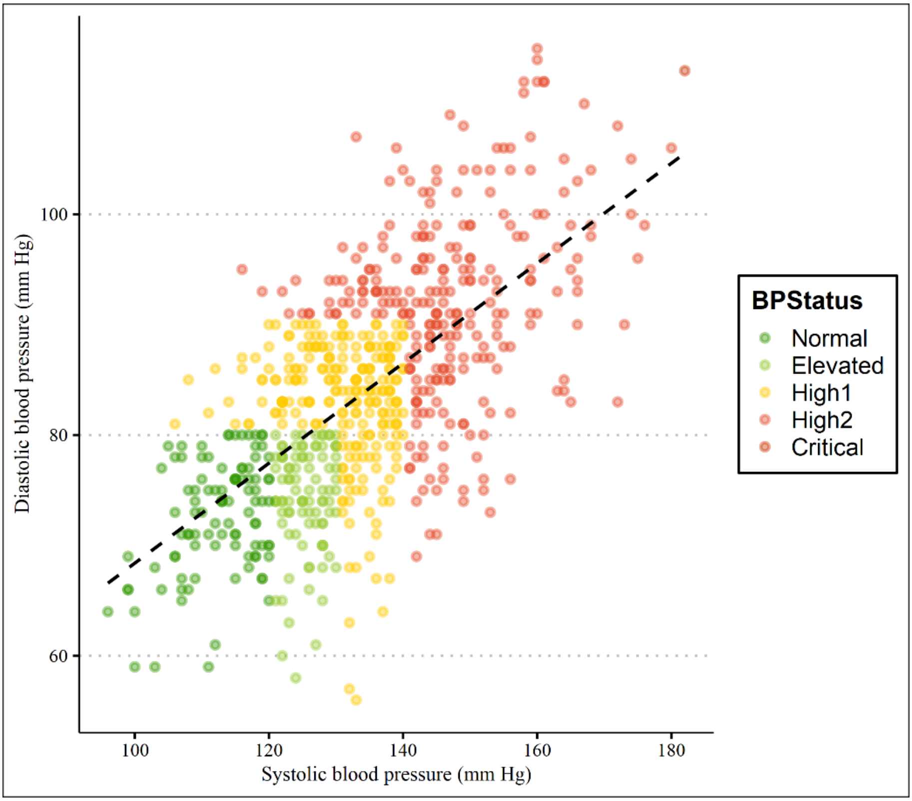

Figure 2-3-3. The association between systolic and diastolic blood pressure among 694 participants. BP status = Blood pressure status according to the American Heart Association "Tools for understanding blood pressure readings" (103). The black dashed line indicates the linear association between systolic and diastolic blood pressure (mmHg). The horizontal dotted lines provide a visual reference for every 20mmHg increase.

2.4. STATISTICS

The statistical analyses conducted over the course of this study were done using SPSS v.23 (IBM Statistics Data Editor, IBM, New York, U.S.A.) for studies II and III, and R v.3.5.3 for Study IV. All data was assessed for normality using Kolmogorov-Smirnov tests and visual analysis of Q-Q plots. Where non-normal distributions were observed in these studies, log transformation was performed in attempt to bring the distributions closer to normal where possible (Study II & III). The threshold for statistical significance was set at 0.05 for all studies.

In study II, the influence of: (a) walking speed measured at self-selected normal and fast speeds and (b) the mobile phone dual-task on (1) spatiotemporal stride parameters, (2) their coefficients of variation, (3) the ratings of perceived exertion (RPE), and (4) the mobile phone task performance was assessed. Average values over three repeated trials were used in final analysis, using a repeated-measure analysis of variance (Study II). In addition, the interaction between walking speed and mobile phone dual-task was assessed. A Bonferroni adjustment was applied post-hoc to account for the effect of repeated trials.

A similar approach was used to analyze the data collected in Study III, since an identical protocol was used. However, in study III, the influence of walking speed and mobile phone dual-task on walking dynamics were investigated. Again, a repeated measures analysis of variance was used, with a post-hoc Bonferroni adjustment (Study III).

In study IV, the association between step quantity and systolic blood pressure was assessed. Separate unadjusted and adjusted regression models were created for daily step quantity, step quantity at work, and step quantity at leisure. A second group of models were created to incorporate information on work and leisure domains.

Adjusted models included potential confounding factors, a priori selected based on their theoretical association with both the exposure and the outcome and through forward-backward selection. Included variables were age, sex (male or female), smoking status (smoker or non-smoker), body mass index (BMI), and the use of antihypertensive medication (Yes or No). Further the models containing domain specific steps were further adjusted measurement hours during leisure, as the number of steps at leisure increased significantly with longer recording periods.

All models were re-run in a sensitivity analysis incorporating information on job type: blue-collar and white-collar.

Finally, the median time spent at a step cadence above and below 100 steps per minute was calculated, as well as the median time spent in each stepping activity (e.g. walking, running, stair climbing). The reader should note that the cadence parameters were initially included in the adjusted models, but subsequently removed during a process of forward and backward selection conducted to supplement the a priori decisions. Moreover, the cadence values available were only derived for walking periods, as such did not match with the step quantities, which were derived using aææ stepping activities.

CHAPTER 3.

A brief overview of the results from studies I-IV is presented in the following chapter, in addition to some interesting results not included in the published manuscripts. For further detail on results reported in published work, please refer to the original studies.

3.1. DUAL TASK COST (STUDY Ⅰ)

The keyword search of the PubMed database yielded 15 experimental studies, 3 observational studies and 1 questionnaire. Gait velocity or walking speed was a primary outcome measure for 8 out of 15 experimental studies. Observed decreases ranged from 7-33% when walking while texting was compared to walking in the single task condition, 19% with an arithmetic task, and 13% for a reading task while walking. Similarly, for stride length there were reported decreases ranging from 2-48% across 6 studies, when walking while texting. Smaller decreases of between 2-6% were observed for arithmetic and reading mobile phone dual task conditions. Few studies reported cadence as a primary outcome measure, but among the 4 studies that did, a decrease in cadence ranging from 4 to 11 % was reported when walking while texting. Again, a small decrease was also observed for a reading task (4%). In conjunction with these decreases, were increase in stride width of between 3 and 14% and an increase in the duration of double support time of between 2 and 15% (Study I). Texting was the primary dual-task investigated. Significant reductions in performance were reported in the dual-task condition, from a reduction in typing speed and accuracy. Alternative cognitive tasks included arithmetic, reading, listening to music, and responses to color cues. The review process highlighted a wide variety of methodological approaches implemented by studies investigating mobile phone dual task. Primary methodological differences included the walking surface, the ecological validity, the level of instruction, the level of stimulus induced by the dual task challenge, and the measures of gait-quality reported (Figure 3-1) (Study I).

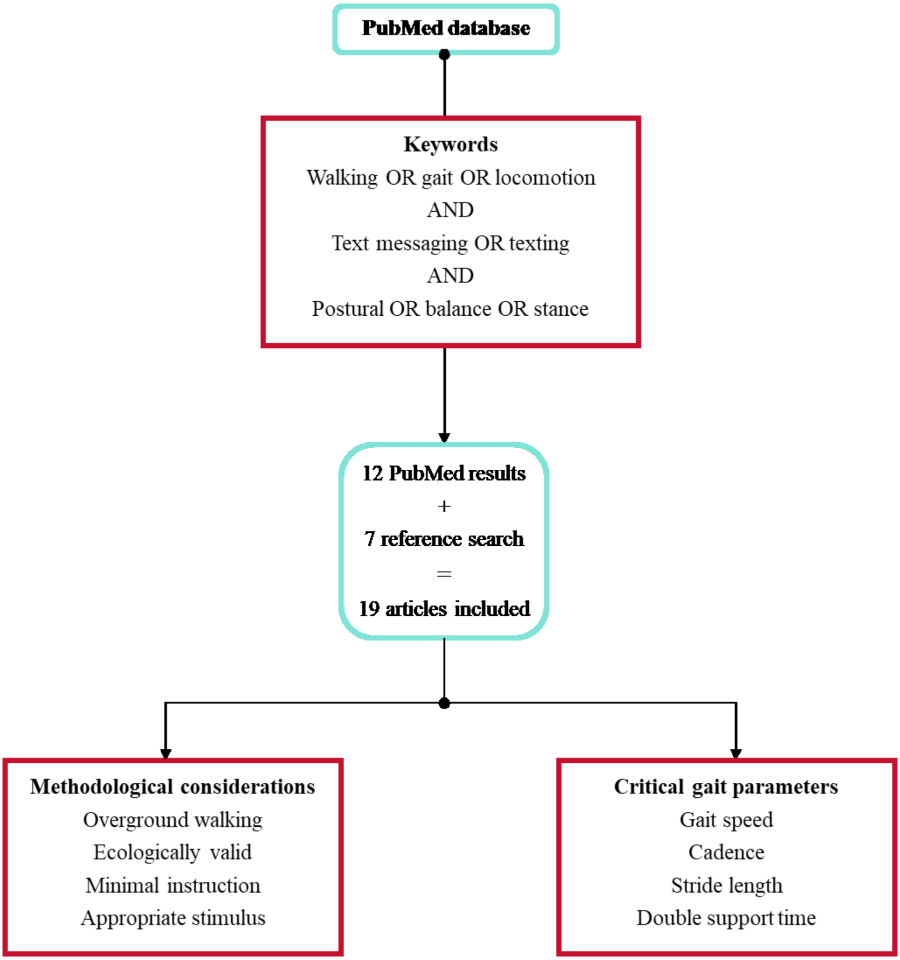

Figure 3-1. Scoping review flow from the keyword search to the main conclusion points.

3.2. THE EFFECTS OF MOBILE PHONE USE ON SPATIOTEMPORAL STRIDE PARAMETERS (STUDY Ⅱ)

Gait velocity, cadence and stride length decreased when texting while walking, whereas double support time increased. Walking while talking on a mobile phone had moderate effects, with a significant decrease in stride length compared with the single task condition. Similar task effects were observed following different walking speed instruction (normal" and "fast") on mean spatiotemporal stride parameters, with an apparent larger decrease/increase observed in the dual task conditions following fast walking speed instruction. Analysis of coefficient of variation values indicated that – with the exception of double support time – there was an increase in variation with the addition of a mobile phone dual task. Texting performance significantly decreased from baseline testing, with an average decrease of 55.5% in the number of characters typed per second on average, when the baseline test was compared to walking while texting. Moreover, when participants were asked to rate the demand of each dual task (following each trial) texting while walking was consistently rated as the most difficult (RPE = 10), followed by the mobile phone dual task (RPE = 9) and finally by the single task condition (RPE = 8) (Study II). A similar trend was evident at a self-selected fast walking speed; RPE = 9, for the single task condition, RPE = 10 for the talking condition, and RPE = 11 for the texting condition (Study II).

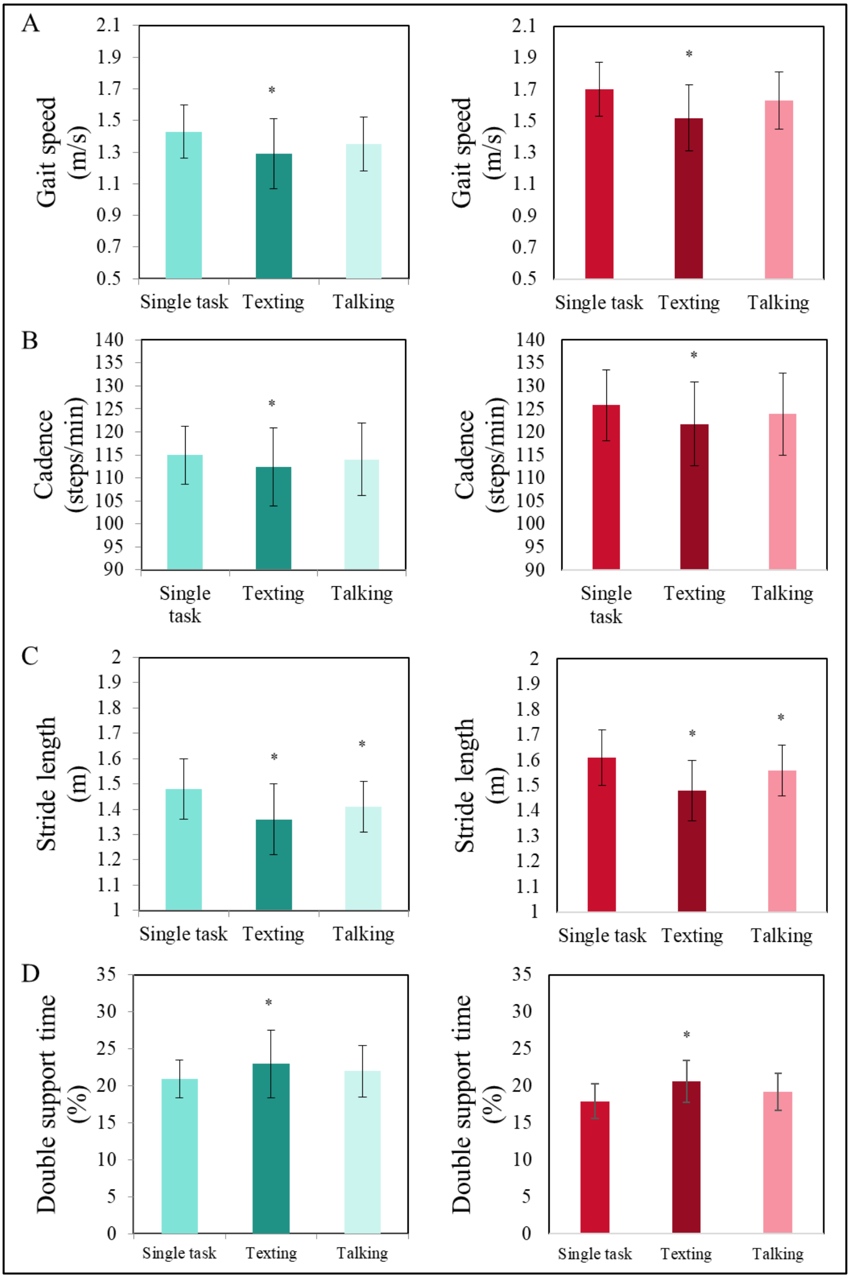

Figure 3-2. Mean spatiotemporal stride parameters of 10 healthy young adults (± 1 standard deviation) for self-selected normal (left column) and fast (right column) walking speeds. (A) Gait speed; (B) Cadence; (C) Stride length; (D) Percentage of the gait cycle in double support. ''denotes $p<0.05$ compared to the single task condition (Study II).*

3.3. THE EFFECTS OF MOBILE PHONE USE ON GAIT DYNAMICS (STUDY Ⅲ)

Analysis of the effect of walking speed instruction on stride time and walking speed are presented in table 3-1. The analysis indicates that participants did walk faster following fast walking speed instruction, as expected and desired. Moreover, that the variation within trials (stride time) was considerably smaller that the variation between trials (walking speed). Analysis of the RMSratio of trunk accelerations following differing walking speed instruction and under dual task conditions, showed a significant effect of walking speed only. There was a significant shift in the ratio of acceleration from the anteroposterior measurement axis to the vertical measurement axis following the instruction to walk at a fast speed. Interestingly, sample entropy was also affected by walking speed where an increase in sample entropy was observed across all measurement axis following a fast walking speed instruction. Task effects were primarily observed for walking while texting. The walking dynamics of walking while talking on a mobile phone appeared similar to those of walking in the single task position. When walking while texting sample entropy decreased significantly along the vertical measurement axis, while the maximum Lyapunov exponent values increased along the vertical and anteroposterior measurement axes (Study III).

	Single task	**Dual task**	
Speed instruction	-	NWS	FWS
Characters typed (n)	36 ± 0.1	74 ± 30	59 ± 32
Percentage errors (%)*	1.9 ± 2.6	1.4 ± 1.3	1.7 ± 1.8
Texting performance (n per second)	2.9 ± 0.7	1.2 ± 0.6	1.2 ± 0.6

NWS = Normal walking speed; FWS = Fast walking speed
*Errors were considered as misspelt words or unnecessary characters. Common texting language was not considered as an error.

Table 3-1. Texting performance of 20 young healthy adults in Study III. (Texting data from 10 participants was published in Study II).

Metric	**Walking only**	**Walking & talking on a phone**	**Walking & texting on a phone**
		NWS	
ST (s)	1.0 ± 0.06	1.0 ± 0.07	1.1 ± 0.07
WS (m/s)	1.7 ± 0.2	1.5 ± 0.2	1.4 ± 0.2
CV ST	4 ± 3	4 ± 3	5 ± 2
CV WS	10	11	12
		FWS	
ST (s)	0.9 ± 0.07	1.0 ± 0.08	1.0 ± 0.08
WS (m/s)	2.0 ± 0.2	1.8 ± 0.2	1.7 ± 0.2
CV ST	4 ± 2	4 ± 2	4 ± 2
CV WS	10	10	12

NWS = self-selected normal walking speed
FWS = self-selected fast walking speed
ST = Stride time
WS = Walking speed
CV = (Standard deviation/Mean)*100
For stride time: CV is calculated as the mean CV for each walking trial

Table 3-2. Average stride time, walking speed and the coefficients of variation of these parameters. The values of 20 young healthy adults are presented as Mean (± 1 standard deviation). (Table adapted from Study III)

3.4. ON THE NUMBER OF STEPS AND BLOOD PRESSURE – THE INFLUENCE OF DOMAIN (STUDY IV)

There was a significant negative association between the quantity of daily steps and systolic blood pressure. Coefficient estimates are presented as estimates per 2000-step interval. Accordingly, a higher daily step quantity was associated with an estimated -0.5 mmHg lower systolic blood pressure (-1.0 to -0.08 95% CI, p = 0.02). When information on work and leisure domains was incorporated, the negative relationship persisted for step quantity at work, whereby a higher step quantity at work was associated with a -0.9 mmHg lower systolic blood pressure (-1.5 to -0.4 95% CI, p = 0.0006). No clear association was found for leisure (+0.1 mmHg per 2000-step interval, -0.7 to 0.9 95% CI, p = 0.75). Further analysis incorporating information on job type (blue-collar or white-collar) no clear association between daily step quantity and systolic blood pressure was observed. When domain was also incorporated, a significant negative association was only observed for blue-collar workers. The association was only significant when the association between step quantity *at work* and systolic blood pressure was considered (-1.1 mmHg per 2000-step interval, -1.7 to -0.4 95% CI, p = 0.0009). No clear association was found among blue-collar workers for the association between step quantity at leisure and systolic blood pressure (+0.3 mmHg per 2000-step interval, -0.6 to 1.2 95% CI, p = 0.5).

No clear associations between step quantity and systolic blood pressure were evident for white-collar workers, neither for daily steps (-0.3 mmHg per 2000-step interval, -1.4 to 0.9 95% CI, p = 0.60), steps at work (-0.3 mmHg per 2000-step interval, -1.7 to 1.1 95% CI, p = 0.68), nor steps at leisure (-0.7 mmHg per 2000-step interval, -2.8 to 1.4 95% CI, p = 0.50) (Study IV). Evident from Figure 3-1, there were considerable differences in the quantity of steps at work between blue-collar (9143 ± 3837 steps) and white-collar workers (5863 ± 3565). Finally, the median time spent at a walking cadence above 100 steps per minute was longer for blue-collar job type at work (57min 28sec, 1st IQR: 40min 55sec; 3rd IQR: 78min 46sec) compared with white-collar workers (34min 48sec, 1st IQR 22min 12sec; 53min 34sec). Walking was by far the dominant stepping activity (Table 3-3), with extremely small durations of running recorded (Table 3-3).

Stepping activity	**Blue-collar** *Median* *(Q1,Q3)*	**White-collar** *Median* *(Q1,Q3)*
At work		
Walking	75min 54sec (55min 30sec, 99min 54sec)	43min 4sec (26min 13sec, 69min 50sec)
Above (100 steps/min)	57min 28sec (40min 55sec, 78min 46sec)	34min 48sec (22min 12sec, 53min 34sec)
Below (100 steps/min)	14min 34sec (8min 20sec, 22min 40sec)	6min 7sec (4min 1sec, 12min 14sec)
Stair climbing	2min 27sec (68sec, 4min 26sec)	75sec (40sec, 2min 13sec)
Running	3.6sec (0, 10.8sec)	0 (0, 3.6sec)
At leisure		
Walking	42min 50sec (31min 1sec, 54min)	42min 50sec (30min 18 sec, 54min 50sec)
Above (100 steps/min)	31min 55sec (23min 31sec, 44min 10sec)	33min 32sec (22min 30sec, 42min 58sec)
Below (100 steps/ min)	9min 5 secs (6min 21sec, 13min 41sec)	9min 11sec (6min 14sec , 11min 56sec)
Stair climbing	1min 55sec (1min 1sec, 3min 3sec)	1min 55sec (57sec, 3min)
Running	4sec (0, 11sec)	4sec (0, 18sec)
Minutes (min); seconds (sec)		

Table 3-3. Time spent in various stepping activities at work and at leisure (i.e. walking, stair climbing and running), as well as, time spent at walking cadence above and below 100 steps per minute. The values of 694 workers are presented as median values, with the 1st and 3rd inter-quartiles, of which 560 blue-collar and 134 white-collar.

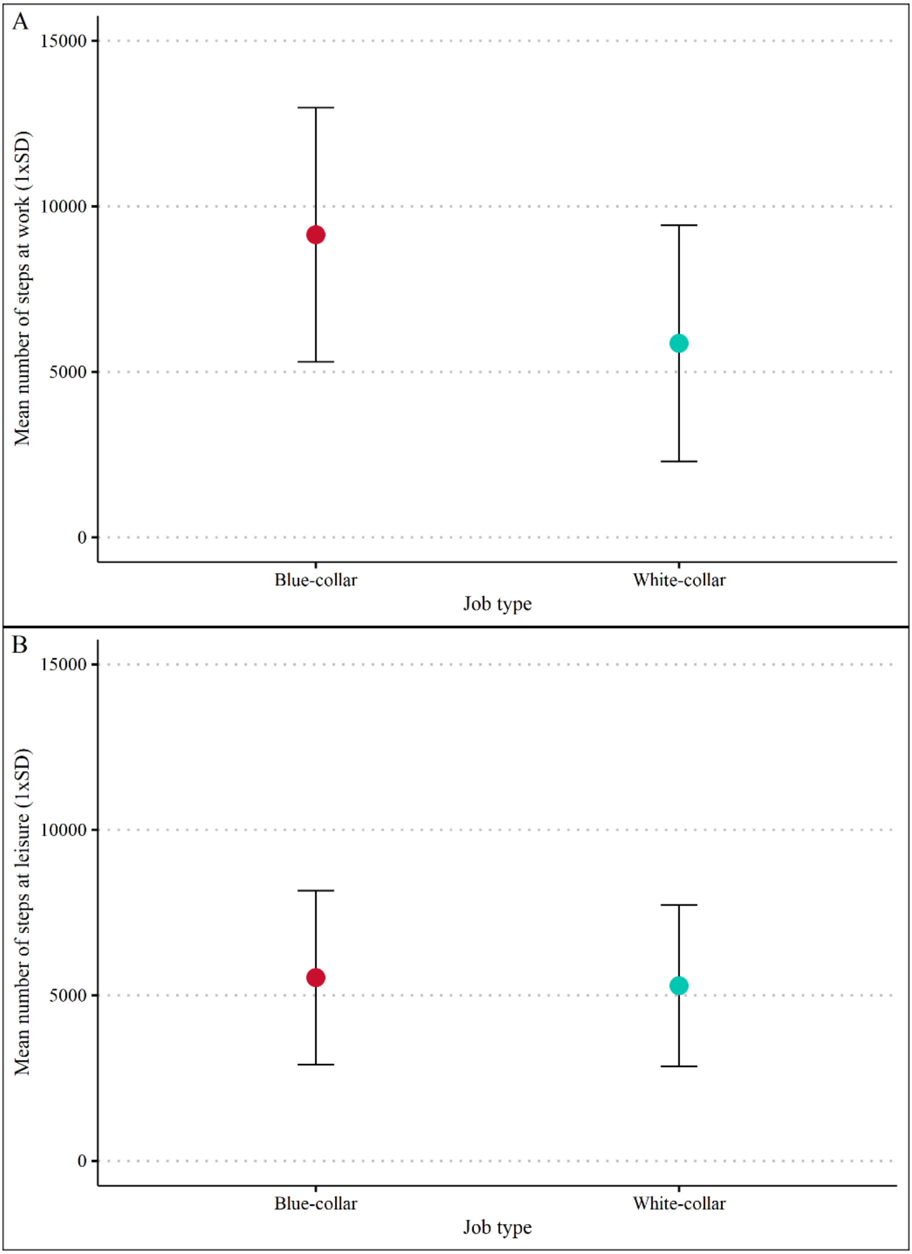

Figure 3-3. The average number of steps ± 1 standard deviation (1 x SD) for 560 blue-collar and 134 white-collar workers at work (A) and at leisure (B).

CHAPTER 4. DISCUSSION

The following Discussion chapter aims to interpret the dissertation findings and set them into perspective. Including considerations on: the measurement of gait-quality, gait-quantity, and the dual task effect (Section 4.1.), the interpretation of the findings (Section 4.2.), the understanding in relation to behavior and health (Section 4.3.), some methodological limitations and considerations (Section 4.4.), overall conclusions (Section 4.5.) and perspectives for future research (Section 4.6.).

4.1. CAPTURING GAIT-QUALITY, QUANTITY & THE DUAL TASK EFFECT

In this section, some considerations for the measurement of gait-quality, gait-quantity and the dual task effect are presented, providing the basis for the methodological decisions taken.

Initially, the scoping review on the effects of mobile phone use during walking (Study I) highlighted a number of key limitations and methodological variations in the existing literature base. Some of these findings were highly specific to the mobile phone dual task, while others are better approached from a broader scientific perspective (e.g. ecological validity). Specific to the mobile phone dual task, there were some clear and seemingly consistent trends in primary spatiotemporal stride parameters observed under mobile phone dual task walking conditions, as well as, stride parameters critical to the dual task effect. Reduced gait speed, stride length, and cadence were all repeatedly reported in the reviewed studies (Study I). Yet the review concluded that discrepancies in the methodological approaches used to measure the dual task effect, made it difficult to determine the full extent of the observed gait changes and the implications (Study I). This general summation of the review findings is also in line with the conclusion of another review on the same topic conducted in parallel (104).

Methodological discrepancies in the measurement of mobile phone dual task persisted down to minor details including the phone holding instruction (105-109), the instruction given for walking speed and the task prioritization (109-111). These factors further detract from the normality of the movement as they affect balance during walking (24, 112, 113).The review further highlighted the lack of ecological validity in many of the implemented protocols - an overarching theme of the methodological limitations (Study I) – thus including fundamental elements linked to the realistic nature of the test conditions, often limited by the technology used for measurement, the walking surface, and the challenge of dual task conditions (Study I). These methodological decisions alone are reported to significantly influence the observed effects of dual task (15, 114) and limit the likelihood of an adequate representation of the natural setting (115). These conclusions went on to influence Studies II-IV in a number of ways. For example, through the selection of over ground walking when measuring the dual task effect on gait-quality. The alternatives, treadmill walking, may alter gait (28, 90) and result in an altered dual task effect (114) (Study II and III). Moreover, this selection allowed participants to select a walking speed that is comfortable for them under each walking condition. Another example is provided in the analysis of gait-quantity, where ecological validity is enhanced through the incorporation of domain and job type information, ensuring that the analysis more accurately reflects everyday routines and behaviors.

To summarize, based on the findings of Study I, considerations regarding the methodological approach, in particular ecological validity, are reflected in core decisions in Studies II-IV.

4.2. INTERPRETING GAIT-QUALITY, QUANTITY, & THE DUAL TASK EFFECT

In this Discussion section, the findings of Studies II-IV will be considered and interpreted together, linking the published studies.

If we consider the measurement of gait-quality and the dual task effect in studies II and III, the selection of over ground walking, a self-selected non-fixed walking speed, and little instruction on how to complete the task, allowed for dual task performance more similar to the everyday life. This is reflected in the relatively small degree of the gait alterations (-7.1% for gait speed, -2.6% for cadence, -7.5% stride length, and + 9.6% for double support time), which are of a lesser degree than studies not prioritizing ecological validity to the same extent (See Study I for the range of alterations observed in previous research). In addition, the protocol design allowed for a degree of movement variability that would not be possible without the freedom to adjust walking speed as required and adapt to changing peripheral information when progressing along the corridor. This again, is reflected in the results, where the CV for each stride parameter vastly increased during mobile phone use compared to the walking only condition: +85% for gait velocity, +52.9% for cadence, +68.4% for stride length, and +21.3% for double support time (Study II).

In Study III, alterations in gait-quality were observed under mobile phone dual task conditions. Increased acceleration magnitude along the vertical axis, a decrease in acceleration magnitude along the anteroposterior measurement axis, an increase in sample entropy values along all measurement axes, and a decrease in local dynamic stability along the vertical measurement axis. Yet, the degree of the alterations was greater than (107, 116), or different from (117) those reported in previous literature (Study III). These comparable studies did not prioritize the ecological validity to the same degree (i.e. preferring treadmill walking and fixed walking speeds) as the studies presented in the current dissertation. Therefore, one could argue that, the observed differences in the findings can be ascribed to gait performance conditions that do not adequately reflect the everyday.

This argument is more difficult to support for performance of the talking and texting task. Although attempts were made to replicate the everyday task through repeated trials, text and conversation topics relating general interests. These attempts were unlikely to have adequately reflected the everyday task, as other important factors such as emotional engagement with the content are unlikely to be replicated. Such factors have been shown to influence dual task performance (118-120). However, texting while walking was consistently rated as the most difficult (RPE = 10), followed by the mobile phone dual task (RPE = 9) and finally by the single task condition (RPE = 8) (Study II). A finding, in line with the reports of previous research (121). However, it must also be mentioned that there is a liklihood that the ratings here, repeated so close one after the other, were affected by the “Tufnel problem” (122). The “Tufnel problem” is the difficulty in obtaining a valid subjective measure of change, over repeated trials (122). As such, the ecological validity aspects of the mobile phone task could definitely be improved

Finally, if we consider the measurement of gait-quantity, as presented in study IV. It can also be argued that the incorporation of domain and job type information in the analysis served as an improvement in the ecological validity of the analysis. Moreover, this is reflected in the novel findings, which would not have been observed without the incorporation domain and job type information.

In summary, the interpretation of the findings relies on important and fundamental methodological decision. In this dissertation the decision was taken to prioritize ecological validity and reflect the everyday as much as possible, yielding novel results that raise important questions, addressed in the next section.

4.3. GAIT-QUALITY, QUANTITY, THE DUAL TASK EFECT & HEALTH

In addition to highlighting the importance of methodological approach and ecological validity, this dissertation also underlines important associations with health the findings imply and raises some interesting and important questions in this regard.

Firstly, the findings related to the dual task effect indicate that mobile phone dual task alters gait-quality even among healthy young adults, without reported cognitive impairment. However, before considering how these findings relate to specifically to health, it is important to raise the questions: what is an unacceptable level of gait performance? And, what degree of gait-quality change indicates this performance level? The answers to these questions are necessarily dependent on the population and environmental constraints investigated and thus will always contain a degree of bias (123). For example, acceptable performance upon request to send an SMS while walking in a quiet corridor is likely to differ considerably from the acceptable performance when crossing the street (110, 124). Equally, the implications of unacceptable performance on health and safety are rather different in either scenario (25, 125). If we then also consider different populations, for example, the elderly or patient groups, the threshold of acceptable performance will differ again, as will the implications for health and safety (126-130). Specifically, the health implications of dual task performance relate to neurodegeneration (126), indicators of general health (127), cognition (128), aging (129) and even the risk of falling (130). The utility then of dual task performance in relation to health can be clearly illustrated through the improvements in health and daily function documented by research on dual task training among wide range of clinical populations (128).

More research is required to illustrate the usage among young adults and to facilitate the interpretation of changes in gait-quality and the extent of the dual task effect in this population. However, promising work already exists, from determining links with health (127), degrees of performance (65) to the clinical diagnoses of injury severity (131)

Secondly, the novel findings of a negative association between step quantity at work and systolic blood pressure among blue-collar workers highlights another important health association, with further important questions raised. Per 2000-step interval, a higher step quantity at work was associated with a lower systolic blood pressure among blue-collar adults of working with a considerable proportion of their daily step quantity occurring at work (Study IV). In contrast, no clear association found among white-collar workers, indicating that there may be a strong role played by socioeconomic factors in the association with health. To provide some perspective as to the relevance of the observed association found among blue-collar workers, just a 2 mm Hg decrease in systolic blood pressure has been linked to a 10% reduction in stroke mortality and 7% reduction in mortality from other vascular causes (13, 132). So clearly, a -1.1 mm Hg lower systolic blood per 2000-step interval has practical implications for health of this group. Also among white-collar workers, who are incredibly sedentary by comparison. This would lay the ground for more and smarter intervention aimed at optimizing step quantity, within productive work. The observation of this association raises fundamental question with regard to “Why is domain not given more importance when considering associations between physical activity and health?” The simple answer is probably due to the lack of current evidence base to date (133), so more empirical research is clearly required.

In summary this dissertation underlines the benefits of gait and dual task research for health, while highlighting the need for more research on gait and dual task performance thresholds and calling for more considered analysis of step quantity in when considering associations with health.

4.4. METHODOLOGICAL CONSIDERATIONS & LIMITATIONS

This subsection will assess some of the limitations association with the reported methodological approach. First, a fundamental methodological decision discussed thoroughly, was the decision to prioritize ecological validity in studies II-IV, which has particular limitations.

In studies II and III, over ground walking was preferred to treadmill walking also justifying the use of accelerometer-base gait measurement. A decision based on the findings of a scoping, not systematic, review. This choice makes it difficult to ensure a “fast” walking speed, as desired, and a difficulty in ensuring a constant gait speed during walking trials. These are inherent limitations of over ground walking and a minimal instruction approach, making this protocol unsuitable for research questions in which a fixed speed is needed. As part of the protocol design in Study II-III, it was only intended that they walk at a speed above their self-determined normal walking speed, thus allowing comparison with their gait at that normal speed - an established method for interpreting gait performance (134). Finally, while the analysis of gait-quantity benefits from the considerable strengths of the DPHACTO cohort, the association between the quantity of steps and systolic blood pressure was investigated in a cross-sectional design, which in turn, limits definite conclusions regarding causation. Moreover, as no detail are provided on the type of activities that are carried out during leisure time and working hours. This does not allow for the precise analysis of gait-quality similar to the analysis in studies II and III.

4.5. CONCLUSION

The measurement and analysis of gait-quality, gait-quantity, and the dual task effect revealed the importance of ecological validity when considering these constructs (Study I). Gait-quality - defined by spatiotemporal stride parameters, variability, regularity and local dynamic stability - showed clear alterations under the mobile phone dual task of texting while walking. The degree of alteration observed while talking on a mobile phone when walking was small and the alterations when texting while walking were significantly larger (Study II & III). Analysis incorporating the information on work and leisure domains, as well as job type, showed that this negative association was only present within the blue-collar job type (Study IV). In summary, this dissertation presents novel information on the role of an everyday dual task on gait-quality, while underlining importance of domain and job type information when considering associations between gait-quantity and health. These novel findings were only possible due to the adopted methodological approach, prioritizing ecological validity.

4.6. PERSPECTIVES

Gait research could benefit from greater collaboration, perhaps implementing some of the proposed next generation of research tools (135). Numerous unanswered questions exist in the field of gait research, not because of the difficulty of the questions, but because of a lack of collaboration between research groups. Collaboration would facilitate larger sample sizes, providing the data required to answer these unanswered questions and allow for the definition of specific reference values of acceptable gait performance (61, 62, 65, 86, 134). Furthermore, greater consideration should be taken when implementing interventions aimed at improving health through gait-quantity. This could take the form of workplace randomized-control-trials taking inspiration from new ideas like the Goldilocks principle (136-138). Incorporating measure of step cadence or even gait-quantity to improve our understanding of the associations between gait and health. Finally, this dissertation lays the ground for the incorporation gait-quality, gait-quantity and the dual task paradigm, therefore, future research should aim to include these constructs in broader clinical, public health and occupational research.

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ISSN (online): 2246-1302
ISBN (online): 978-87-7210-887-2
AALBORG UNIVERSITY PRESS