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Neuroscience, Psychological and Psychiatric Sciences, And Movement Sciences

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TITLE OF THE DOCTORAL THESIS

The digital challenge for physical activity.
Quantitative and qualitative monitoring of Nordic Walking activity.

S.S.D. M-EDF/02

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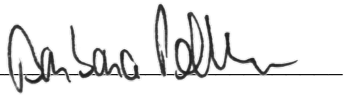
Signature 

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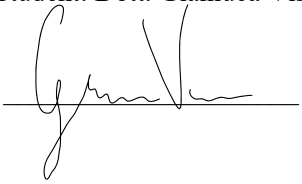
Signature 

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SOMMARIO

Il Nordic Walking (NW) è diventato sempre più popolare negli ultimi anni, sia come disciplina per migliorare il livello di fitness e promuovere la salute negli individui sani, sia per contrastare gli effetti negativi della maggior parte delle malattie croniche non trasmissibili sensibili all'esercizio fisico. Ma, come evidenziato in letteratura, la corretta esecuzione della tecnica del NW pare essere un fattore rilevante per massimizzare gli effetti positivi associati alla pratica che la ricerca scientifica sta caratterizzando. Da qui nasce la necessità di utilizzare e sviluppare ulteriormente nuove tecnologie specificatamente sviluppate per monitorare i parametri biomeccanici della pratica del NW, insieme ai tradizionali parametri metabolici legati all'attività. Questo approccio è conseguente a quanto osservato negli ultimi anni, ovvero al crescente utilizzo della tecnologia commerciale nei diversi ambiti della salute, dell'esercizio fisico e dello sport. È inoltre fondamentale comprendere come tali strumenti possano supportare la pratica quotidiana dei professionisti del movimento, permettendo il monitoraggio delle attività svolte dagli utenti e fornendo feedback, anche a distanza, ampliando così le possibilità di analisi, migliorando la precisione delle valutazioni e favorendo lo sviluppo di interventi più mirati ed efficaci. Da questa esigenza nasce l'idea di Gabel S.r.l. di sviluppare un sistema in grado di affrontare tali sfide, che si concretizza in un bastoncino da NW strumentato chiamato E-Poles, affiancato da un'applicazione mobile e un portale web dedicati. Questo sistema comprende una coppia di bastoncini capaci di acquisire, elaborare e gestire una vasta gamma di parametri biomeccanici rilevabili durante l'attività di NW, fornendo così informazioni dettagliate sul gesto tecnico. La piattaforma digitale associata consente inoltre di monitorare i progressi nel tempo, di analizzare i dati in maniera integrata e di fornire feedback immediati, facilitando l'ottimizzazione della pratica e l'adozione di interventi personalizzati per migliorare la performance e la sicurezza dell'attività.
Questa tesi di dottorato dunque ha come scopo principale fornire un supporto scientifico all'ulteriore sviluppo della strumentazione già in sviluppo da parte dell'azienda cofinanziatrice del dottorato, integrando parametri e valutazioni

sempre più avanzati e specifici. Ciò tramite la valutazione della sua validità ed efficacia attraverso una serie di test, esperimenti e raccolte di dati riguardanti sia l'utilizzo di diversi tipi di bastoni su un gruppo di praticanti di NW che sugli effetti dell'utilizzo degli E-Poles su diverse popolazioni. Parallelamente, attraverso il progetto, sono state fornite indicazioni per ottimizzarne l'accessibilità e proposte e suggerimenti o idee mirate per il miglioramento dell'app dedicata e del portale di servizio. Nello specifico, nello **studio 1**, sono stati analizzati diversi aspetti dell'uso di tre tipi differenti di bastoni da Nordic Walking. In particolare, ci si è concentrati sulla biomeccanica del cammino, sulle risposte metaboliche e sull'attivazione muscolare, senza trascurare la percezione soggettiva dei partecipanti durante l'utilizzo dei tre diversi bastoni. I risultati indicano che il classico tipo di bastone da NW, modello sul quale è anche basato l'E-Poles, resta ancora la scelta migliore. Successivamente con lo **studio 2**, ci si è concentrati maggiormente nell'indagare eventuali effetti e/o differenze nell'apprendimento della tecnica di NW, utilizzando il sistema ideato da Gabel S.r.l., l'E-Poles, in 2 diverse popolazioni, un gruppo di sopravvissute al carcinoma della mammella (BCS) ed un gruppo di donne in salute (HW). I risultati indicano che l'utilizzo degli E-Poles può essere considerato un potenziale strumento di monitoraggio sia per le BCS sia per le HW. Tuttavia, sono necessari ulteriori studi per confermarne l'efficacia e definirne con maggiore precisione le applicazioni pratiche. È comunque emerso che l'impiego di questa tecnologia ha contribuito positivamente al mantenimento dell'aderenza al programma di allenamento. Ed infine lo **studio 3**, realizzato in contemporanea allo studio 2 e sulla stessa popolazione ma con un obiettivo differente, quello di indagare l'effetto di un programma di esercizio fisico basato sul Nordic Walking su aspetti di forza, flessibilità ed equilibrio. In questo caso i risultati confermano l'effetto positivo della pratica del NW come forma di esercizio total body, già ampiamente descritto in letteratura, ma mostrano anche che in presenza di una condizione patologica un programma di esercizio fisico può richiedere più tempo per avere gli stessi effetti che su una popolazione in salute.

I risultati di questa tesi di dottorato sono quindi finalizzati ad approfondire gli effetti nell'uso di diversi tipi di bastoni da NW, indagare come dei bastoni elettronici possono essere inseriti nei programmi di esercizio strutturati e con la partecipazione di diversi tipi di popolazioni, nonché a valutare gli effetti del NW su diversi ambiti della salute.

ABSTRACT

Nordic Walking (NW) has become increasingly popular in recent years, both as a discipline to improve fitness levels and promote health in healthy individuals, and as a means of counteracting the negative effects of most non-communicable chronic diseases that are sensitive to physical exercise.

However, as highlighted in the literature, the correct execution of the NW technique appears to be a relevant factor for maximizing the positive effects associated with the practice that scientific research is characterizing. This raises the need to utilize and further develop new technologies specifically designed to monitor the biomechanical parameters of NW practice, in conjunction with traditional activity-related metabolic parameters. This approach is consistent with recent observations, which have shown an increasing use of commercial technology in various fields, including health, physical exercise, and sport. It is also essential to understand how such tools can support the daily practice of movement professionals, allowing the monitoring of the activities carried out by users and providing feedback, including remotely, thus expanding the possibilities for analysis, improving the accuracy of assessments, and promoting the development of more targeted and effective interventions.

From this need arose the idea of Gabel S.r.l. to develop a system capable of addressing these challenges, which materializes in an instrumented NW pole called E-Poles, accompanied by a dedicated mobile application and web portal. This system comprises a pair of poles capable of acquiring, processing, and managing a wide range of biomechanical parameters that can be detected during NW activity, thus providing detailed information on the technical gesture. The associated digital

platform also enables the monitoring of progress over time, the analysis of data in an integrated manner, and the provision of immediate feedback, thereby facilitating the optimization of practice and the adoption of personalized interventions to improve performance and the safety of the activity.

This doctoral thesis, therefore, has as its primary purpose to provide scientific support for the further development of the instrumentation already under development by the company, which is co-funding the doctorate, by integrating increasingly advanced and specific parameters and assessments. This is achieved through the evaluation of its validity and effectiveness using a series of tests, experiments, and data collections, which concern both the use of different types of poles among a group of NW practitioners and the effects of using E-Poles in various populations. In parallel with the project, indications were provided to optimize its accessibility, as well as proposals and targeted suggestions or ideas for improving the dedicated app and the service portal.

Specifically, in **Study 1**, various aspects of the use of three different types of Nordic Walking poles were analyzed. In particular, the focus was on gait biomechanics, metabolic responses, and muscle activation, while also considering the subjective perception of participants during the use of the three different poles. The results indicate that the classic type of NW pole, the model on which E-Poles is also based, still remains the best choice. Subsequently, with **Study 2**, the focus shifted more towards investigating possible effects and/or differences in the learning of the NW technique, using the system devised by Gabel S.r.l., E-Poles, in two different populations: a group of breast cancer survivors (BCS) and a group of healthy women (HW). The results indicate that the use of E-Poles is a potential monitoring tool for both BCS and HW. However, further studies are needed to confirm its effectiveness and to define its practical applications more precisely. It nevertheless emerged that the use of this technology contributed positively to maintaining adherence to the training program. And finally, **Study 3**, carried out concurrently with Study 2 and on the same population, but with a different objective: to investigate the effect of an exercise program based on Nordic Walking on aspects of strength, flexibility, and balance. In this case, the results confirm the positive

effect of NW practice as a total-body form of exercise, already widely described in the literature, but also show that, in the presence of a pathological condition, an exercise program may require more time to have the same effects as in a healthy population. The results of this doctoral thesis are therefore aimed at deepening the understanding of the effects of using different types of NW poles, investigating how electronic poles can be incorporated into structured exercise programs involving various populations, and evaluating the effects of NW on different domains of health.

MANUSCRIPT IN PREPARATION

***G. Viscioni**, A. Di Blasio, L. Ditali, S. Bettega, F. Schena, L. Bortolan, B. Pellegrini*. Learning Nordic Walking Technique with Sensorized Poles and Automated Feedback in Breast Cancer Survivors and Healthy Women: A Pilot Comparative Study

***G. Viscioni**, L. Ditali, F. Schena, L. Bortolan, B. Pellegrini*, *A. Di Blasio.* Effects of an 8-week Nordic Walking program on functional capacity, balance, and flexibility in breast cancer survivors and healthy women

ORAL COMMUNICATIONS

***G. Viscioni**, B. Pellegrini, F. Schena, L. Bortolan*
Muscular engagement, metabolic responses and subjective perception with different types of Nordic Walking poles. SISMES XIV National Congress.
Chieti, 19 – 21 Sep 2024

G. Viscioni.
E-Poles e Donne trattate per Tumore Mammario: Opportunità, Evidenze e Prospettive Future. EXPOSANITÀ 2024 HEALTH CARE INNOVATION.
Bologna, 17 – 19 Apr 2024

POSTERS

***G. Viscioni**, A. Di Blasio, S. Grosso, T. Morano, F. Lancia, A. Di Marco, P. Izzicupo, S. Grossi, B. Pellegrini, G. Napolitano, A. Di Baldassarre.*

Technical effects of the combined use of technology and feedback on Nordic Walking technique of breast cancer survivors and healthy women.

SISMES XIV National Congress. Napoli, 2 – 5 Nov 2023.

Honorable Mention – Poster Presentation, Young Researcher Award

***G. Viscioni**, M. Meneghetti, E. Dimo, E. Feola, C. Zoppirolli, B. Pellegrini, A. Calanca, L. Bortolan.*

A supervised machine learning approach for technique identification in cross-country skiing using pole-embedded IMU sensors.

10th ICSS – International Congress on Science and Skiing. Val di Fiemme, 28 Jan-1 Feb 2025.

ABBREVIATIONS

NW Nordic Walking

BCS Breast Cancer Survivors

HW Healthy Women

INWA International Nordic Walking Federation

ANWI Associazione Nordic Walking Italia

NWP Classic Nordic Walking Pole

WP Wheel Pole

TWP T-handle Wheel Pole

EMG Electromyography

ES Erector Spinae

LD Latissimus Dorsi

AD Anterior Deltoid

PD Posterior Deltoid

BB Biceps Brachii

TB Triceps Brachii

FCR Flexor Carpi Radialis

ECR Extensor Carpi Radialis

HC Comfort of handle

PE Push effectiveness

PR Comfort during recovery

PH Ease of pole handling

CT Cycle Time

ROM Range of Motion

MVC Maximum Voluntary Contraction

BCS-ST Breast Cancer Survivors Standard Poles

HW-ST Healthy Women Standard Poles

BCS-EP Breast Cancer Survivors E-Poles

HW-EP Healthy Women E-Poles

PCT Pole Contact time

DC Duty Cycle

1 BACKGROUND AND GENERAL AIMS

1.1 Nordic Walking

Nordic Walking (NW) is a form of walking that integrates the active use of two specially designed poles, intended to coordinately engage the upper-body musculature during gait. The discipline originated in Finland; the earliest documented accounts of walking with ski poles date back to 1966, as a summer variant of cross-country skiing, which allows athletes to maintain their conditioning out of season by incorporating pole-assisted walking and running during the off-season. By the mid-1990s, the first scientific publications on pole-assisted walking appeared; since then, NW has spread worldwide. Concurrently, the International Nordic Walking Federation (INWA) was established as the discipline's global governing body, formally endorsed by the originators to promote, advance, and safeguard its core principles worldwide. (*INWA NORDIC WALKING*, s.d.)

According to the INWA, the official definition of Nordic Walking is as follows: Nordic Walking is an intensification of natural walking through the active use of a pair of purpose-built Nordic Walking poles, which preserves the characteristics of natural walking, including biomechanical correctness and appropriate posture. (Maas et al., 2023)

This description highlights a key point: NW does not aim to modify walking, but to amplify its positive aspects thanks to the use of poles, which are not merely a simple support; they become an active part of the movement. These characteristics lead to a series of peculiar effects from a functional perspective. Over time, NW spread rapidly, with a consequent rise in scientific interest, and is now practiced both as a fitness activity and in prevention and rehabilitation settings.

1.2 Technical Execution

Before examining the functional and social aspects of NW, it is essential to begin with a description of the movement technique.

During walking with poles, a natural rhythm should be maintained, characterized by a smooth and harmonious movement of the upper and lower limbs. The technique relies on the same "opposite arm–leg" coordination typical of normal gait. The arms should never extend forward beyond what occurs during brisk walking without poles. With each step, the pelvis rotates and is accompanied by a counter-rotation of the contralateral shoulder; consequently, the arms swing alternately forward and backward. During each step, the pole is held obliquely, and the tip of the pole is planted behind the body and used to generate propulsive force, engaging the upper-limb musculature. The hand closes during the push phase/pooling phase and opens during the release/recovery phase. Active, controlled trunk movements together with proper postural alignment and good core stability are fundamental components of the NW technique (Maas et al., 2023). Arm motion must be synchronized with trunk rotation, which is a natural effect of lower-limb movement. From this, the three main points of correct NW technique can be summarized:

1. Correct posture and body alignment, core stability, and active, controlled, natural trunk movements
2. Proper walking technique
3. Proper technique for using the poles

The coordinated integration of these three aspects is the basis for the functional benefits of NW and, more broadly, for its positive effects.

From a biomechanical perspective, walking with poles can be described using specific spatiotemporal and angular parameters as is normally done in gait analysis. In the case of NW, of course, the description of lower-limb movement is accompanied by that of the upper limbs, which is specific to this activity.

Each pole performs repetitive cycles, defined as the interval between two consecutive ground contacts of the same pole; the duration of this interval is referred to as pole cycle length. Within each cycle, two main phases can be identified: a poling phase and a recovery phase.

The poling phase extends from pole–ground contact to pole take-off and corresponds to the time during which the pole generates propulsive force. The recovery phase, on the other hand, corresponds to the forward swing of the pole from take-off until the next ground contact (Krejčí et al., 2013; Pellegrini et al., 2018). The longer the duration of the poling action, the greater the involvement of the upper-body musculature and the joint range of motion (Pellegrini et al., 2018). The duration of the poling phase should be sufficiently long to ensure that the duty cycle, calculated for each side as the percentage of the cycle duration spent in the poling phase, is at least 50% or slightly longer. This requirement, together with proper synchronization between the movements of the left and right poles, ensures that one pole remains in contact with the ground at all times. This would be beneficial for ensuring a stronger base of support, a factor relevant for practitioners with balance problems (Pellegrini et al., 2022).

Another key parameter is the inclination of the pole (**Fig.1**), which is the angle formed by the pole and the ground in the sagittal plane with respect to the horizontal line, typically considered at ground contact and/or during the poling phase (Mocera et al., 2018; Pellegrini et al., 2018).

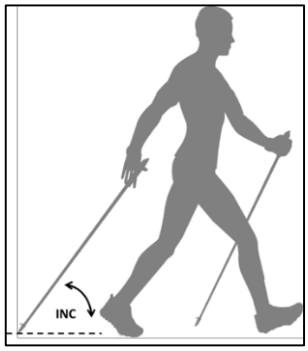

Fig. 1. Angle formed by the pole and the ground.

In a correct NW pattern (**Fig.2**), the poles are placed with a backward inclination at contact and maintain an oblique position during the poling phase, allowing for a more effective transfer of force through the upper limbs compared to when the poles are planted more vertically (Pellegrini et al., 2018).

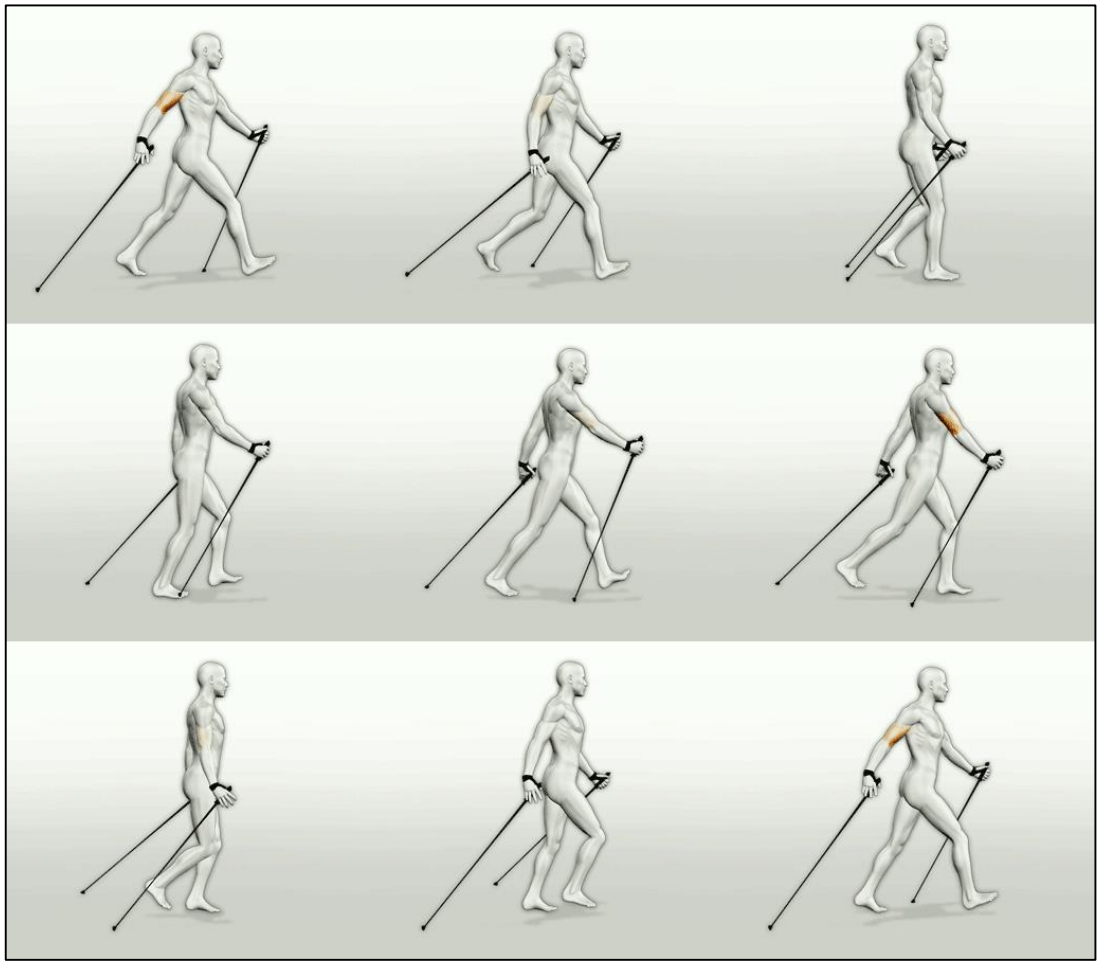

Fig. 2. Sequence of the Nordic Walking technique: consecutive frames of a gait cycle.

1.3 Nordic Walking in Scientific Research

Although Nordic Walking is a relatively young discipline, its scientific evidence base has expanded considerably in recent decades, in parallel with its growing adoption as a form of physical activity. Sport science research has progressively explored its effects from multiple perspectives, including performance, biomechanics, health promotion, rehabilitation, and motor learning. Part of this

doctoral project also involved expanding a database cataloguing scientific articles on NW. The literature search was conducted in databases including PubMed, Scopus, and Web of Science, and the results were subsequently made publicly available on the website of the Italian section of the INWA, the Associazione Nordic Walking Italia (ANWI) (*ANWI - Database*, s.d.). From this database, almost 521 scientific publications on NW were identified between 2000 and 2024. In the early years, output was limited, with only 22 studies published between 2002 and 2009, primarily focused on the physiological effects of NW. The number of papers increased to 86 in the period from 2010 to 2014, to 186 between 2015 and 2019, and reached 225 publications in the years 2020–2024. The publications focused on a wide range of domains, from a biomechanical perspective to more pathological-related assessments. Some investigations focus on the biomechanical and physiological characteristics of Nordic Walking, while others examine the effects of a training period with Nordic Walking compared to traditional fitness programs.

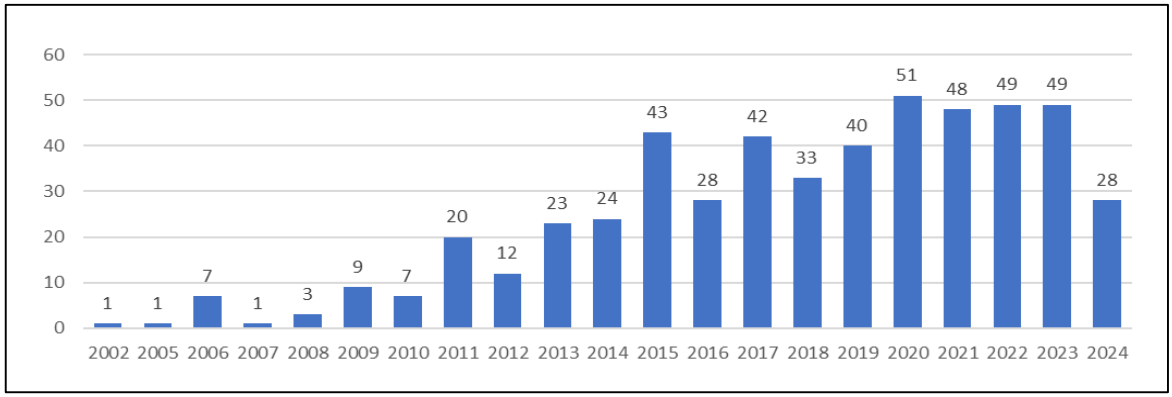

Fig. 3. Number of scientific papers for the year of publication.

This temporal trend clearly illustrates he progressive growth of NW within the field of sport science research, and this expansion of the literature has been accompanied by a broadening of the target populations and research questions. At the beginning of 2025, approximately 62% of the studies involve pathological populations (322 articles), while about 38% focus on healthy individuals (199 articles).

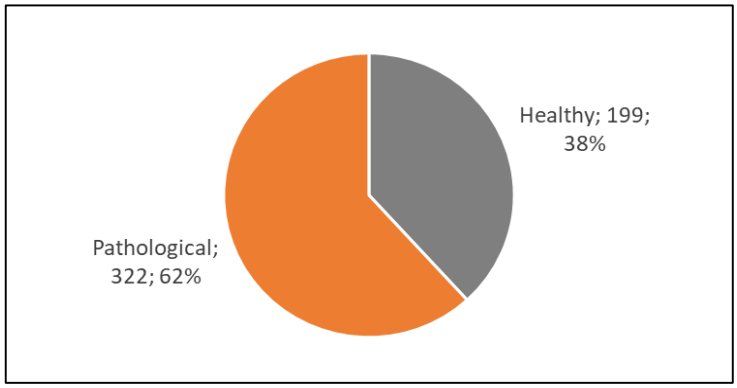

Fig. 4. Conditions of subjects.

When considering only studies conducted in pathological populations, the literature can be broadly organized into a few main clinical macro-areas, with the cardiovascular and metabolic domain having the highest number, followed by the neurological, osteoarticular, and oncological domains. Recently also the respiratory and psychological areas have also been reported.

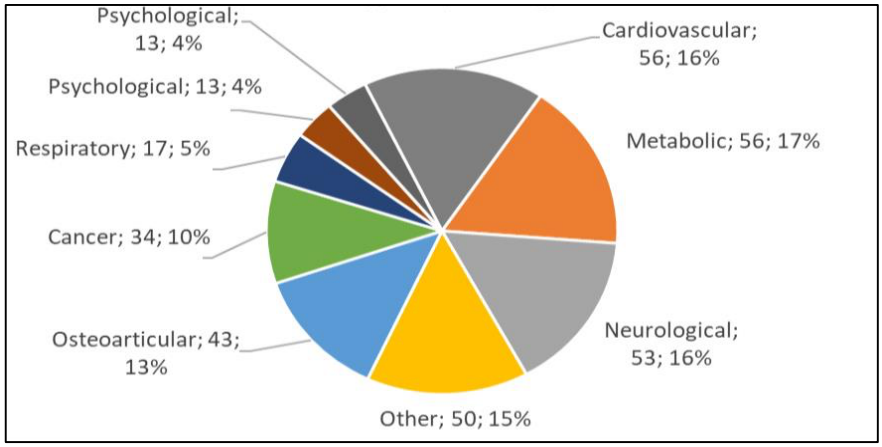

Fig. 5. Macro-areas of health conditions.

The age range of participants is also consistent with NW being positioned as an accessible form of exercise across adulthood. Most studies were conducted in adult populations, followed by a large number of investigations in senior populations, with only a small proportion of studies specifically targeting younger individuals.

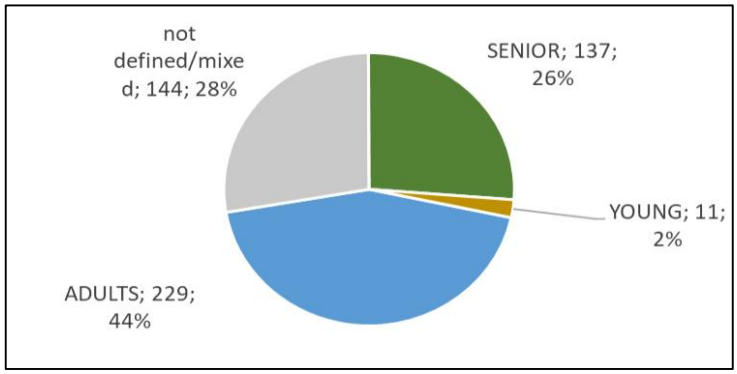

Fig. 6. Age categories

From a geographical perspective, the research output is not restricted to a single country or region: a substantial number of studies originate from European countries, with Poland who are leading in terms of the number of publications, but also important contributions are from North America and Asia with Canada and Japan leading respectively, confirming that NW has been adopted and investigated in diverse cultural and healthcare contexts.

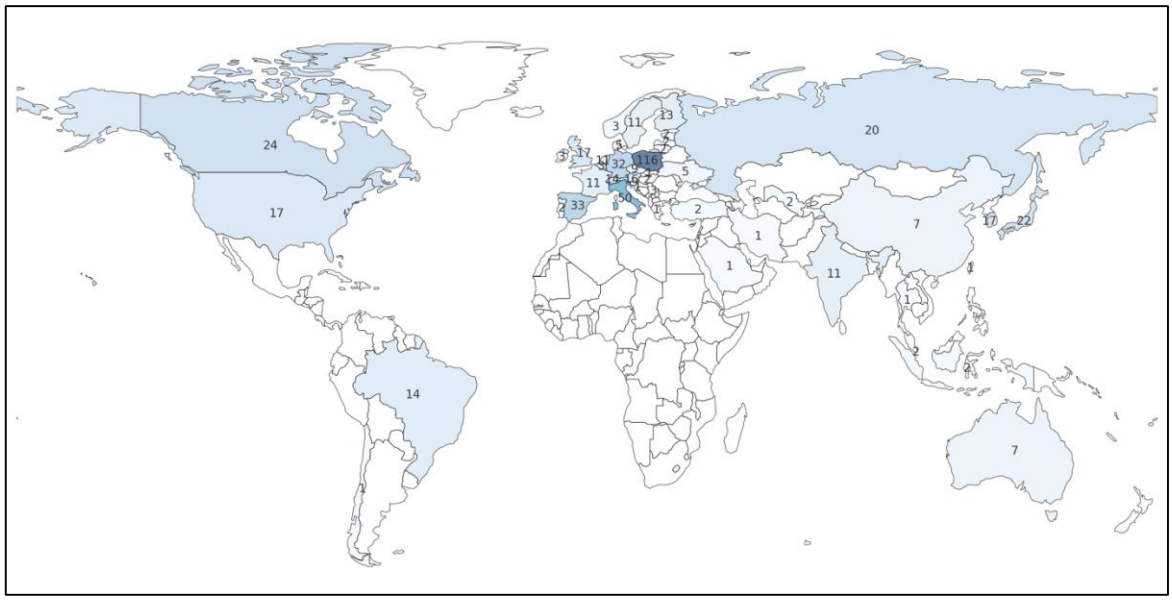

Fig. 7. World map with the geographical distribution of the included articles by country. Countries are encoded using a sequential colour scale, with higher article counts represented by progressively darker shades; numeric labels indicate the exact number of articles per country. (Illustration generated using artificial intelligence)

Taken together, these numbers indicate that NW is now an increasingly well-established topic within the field of sport and exercise science, supported by a growing and diversified body of literature. Building on this quantitative overview, the following section will focus more specifically on the physiological and biomechanical responses associated with NW.

1.4 Physiological and Biomechanical Characteristics

From the physiological perspective, NW results in increased energy expenditure and a greater cardiovascular response compared to traditional walking. Pioneering studies such as those by Porcari et al. (1997) found that walking with poles resulted in an average of 23% higher VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$), 22% higher caloric expenditure ($kcal \cdot min^{-1}$), and 16% (bpm) higher heart rate responses compared to walking without poles on a treadmill. Jordan et al. (2001) and Church et al. (2002) confirmed the same; NW, examined in the field, results in a significant increase in oxygen use and caloric expenditure compared to regular walking. These results provided the first evidence of the physiological characteristics of the NW. More recently, the study by Pellegrini et al. (2015) confirmed these findings; in level walking, VO2 was 22.6% greater during NW than during walking. However, the same study from Pellegrini et al. (2015) shows that these differences tend to narrow when comparing NW with ordinary walking on an uphill slope.

Another interesting aspect, as noted in the study by Church and colleagues (2002), is that despite requiring greater oxygen consumption, the perceived exertion (RPE) during the NW is not significantly higher. The same results about the oxygen consumption and the perceived exertion (OMNI scale) were also confirmed later by Sugiyama et al., (2013).

From a different point of view, the increased energy expenditure can be attributed to the active involvement of upper-body muscles. A different pattern of muscle activation in NW compared with normal walking was indeed shown by Sugiyama et al. (2013) and Pellegrini et al. (2015). The muscle activation of the upper extremities has been found to be higher during NW. More specifically, EMG signals have been found to be higher in the triceps brachii, in the latissimus dorsi, the biceps brachii, and the anterior deltoid. During the poling phase, the triceps brachii and latissimus dorsi are the primary contributors, producing elbow and shoulder extension. The biceps brachii and anterior deltoid remain active across the whole gait cycle; during the pole recovery phase, the biceps brachii serves to flex the elbow, and the deltoideus anterior medially rotates and stabilizes the shoulder.

They are probably not only involved in pole recovery during the arm swing phase but also work in coactivation with the triceps brachii and latissimus dorsii muscles during the poling phase.

A further characteristic of NW, as far as muscle engagement, is that while it shares four muscle synergies with conventional walking, those involving the lower limbs and trunk, it also recruits an additional NW-specific synergy that helps to gain extra postural and physiological benefits. This synergy, linked to the upper-limb propulsion, reorganizes the spatial pattern and magnitude of upper-limb muscle activation compared with conventional walking, without increasing motor control complexity or disrupting lower-limb coordination. In brief, after a period of familiarization, coordination during NW does not feel more difficult than normal walking. (Boccia et al., 2018).

Shifting the focus toward biomechanics, comparative studies conducted to characterize the kinematics reported greater cycle length for NW than for walking at the same speed (Dziuba et al., 2015; L. Hansen et al., 2008), and higher self-selected speed has been reported for walking with poles (Willson et al., 2001; Encarnación-Martínez et al., 2015). However, it is essential to emphasize that these effects may change if the execution techniques differ from the one defined as the INWA's style, as described in the technical execution paragraph. Indeed, when altered styles are adopted, as investigated by Pellegrini et al. (2017) asking NW instructors to deliberately adopt these, a consistently lower EMG activation in key shoulder extensors (latissimus dorsi, posterior deltoid, triceps brachii), shorter step length, and overall lower oxygen uptake than with the recommended technique was observed; by contrast, the correct technique increased VO_2 at the same walking speed and raised upper-body muscle activation.

On the same line, Homma et al. (2016), who compared a Japanese-style NW technique, characterized by a more vertical pole position, with a European-style technique in adults with hip osteoarthritis and showed reduced pelvic rotation and lower hip and trunk muscle activation in the Japanese style, thereby confirming that different technical styles can substantially modify the biomechanical response to NW.

To conclude, these physiological and biomechanical characteristics have likely contributed to the widespread adoption of NW as a form of physical activity. The next chapter, therefore, focuses on the health benefits of Nordic Walking–based programs.

1.5 Health Benefits of Nordic Walking-based Programs

As anticipated in the previous chapter, the scientific literature on NW has grown substantially over the last twenty years, the earliest publications (Rodgers et al., 1995; Porcari et al., 1997; Church et al., 2002), dating to the late 1990s and early 2000s, focused primarily on the physiological effects of NW, aiming to verify whether the use of poles yielded measurable physiological and performance-related benefits. In subsequent years, research progressively broadened to more detailed analyses of biomechanical and neuromuscular aspects, with studies investigating coordination and kinematic changes relative to conventional walking (Willson et al., 2001; Sugiyama et al., 2013; Pellegrini et al., 2017; Boccia et al., 2018; Pellegrini et al., 2018). This body of work helped clarify how proper technique and synchronized movements are crucial to maximizing the benefits of NW.

Starting from this point, an increasing number of intervention studies have examined the health effects of NW-based programs in clinical populations, and several systematic reviews and meta-analyses have now synthesized these findings across specific domains.

Some of the first literature reviews already attempted to summarize the health-related effects of NW across different domains. One of the earliest systematic reviews identified 26 studies published between the mid-1990s and 2009, classifying them into physiological, rehabilitation, and biomechanical research, and emphasizing that several of the widely promoted benefits of NW were only partially confirmed by the available data (Morgulec-Adamowicz et al., 2011). While the results were heterogeneous and sometimes discrepant, especially for acute physiological responses under different testing conditions, findings from rehabilitation studies in cardiology and peripheral arterial disease consistently supported the use of NW as a safe and effective adjunct in patients after myocardial

infarction, coronary artery disease, or intermittent claudication. A subsequent systematic review focusing on health outcomes reported 16 randomized controlled trials and 11 observational studies, and concluded that NW exerts beneficial effects on resting heart rate, blood pressure, exercise capacity, maximal oxygen consumption and quality of life in various patient groups, with responses that were at least comparable to brisk walking and, for some endpoints, even to jogging (Tschentscher et al., 2013). These early syntheses positioned NW as a feasible option for primary and secondary prevention in populations at increased cardiovascular risk, while also underlining the need for more rigorous and disease-specific research.

In parallel, a narrative review specifically addressing Nordic Walking in the "second half of life" summarized evidence from 27 randomized and controlled studies in older adults with age-related diseases (Skórkowska-Telichowska et al., 2016). Across conditions such as coronary artery disease, chronic heart failure, lower-extremity arterial disease, metabolic syndrome without diabetes, chronic obstructive pulmonary disease, early-stage Parkinson's disease, Sjögren's syndrome, and chronic low back pain, NW was reported to improve exercise capacity, walking distance, functional status and health-related quality of life, often with additional benefits on mood and depressive symptoms. In that context, NW was described as a safe, accessible, and well-tolerated form of exercise for older adults, typically implemented in supervised sessions of about one hour, two to three times per week over at least three months, and proposed both as a way to increase everyday physical activity and as a component of long-term rehabilitation programs. These early reviews provided an initial picture of the potential health applications of NW, while also highlighting the need for further investigation. In the following years, this gap began to be addressed through systematic reviews and meta-analyses that focused on specific populations and outcomes, providing a more detailed and quantitative synthesis of the health effects of NW-based programs.

To be more specific, in oncology, from two recent reviews on 10 RCTs and 4 uncontrolled studies, NW emerges as a feasible and safe option that can improve upper-body function, shoulder mobility, lymphedema-related outcomes, cancer-related fatigue, and health-related quality of life in women with breast cancer, particularly when integrated into supervised exercise programs (Sánchez-Lastra et al., 2019; Casanovas-Álvarez et al., 2025).

In people with overweight and obesity (17 RCTs and 5 uncontrolled trials), NW interventions consistently induce favourable changes in anthropometric and body-composition indices (e.g., body mass, BMI, waist circumference) and improve aerobic capacity, often with effects comparable or superior to those of conventional walking programs (Gobbo et al., 2019; Sanchez-Lastra et al., 2020).

Neurological and neurodegenerative populations also appear to benefit, in Parkinson's disease (12 RCTs) NW has been associated with improvements in motor symptoms, gait parameters, balance and functional mobility, together with gains in quality of life (Salse-Batán et al., 2022), while in older adults NW shows a significant positive effect on executive function, particularly in those with health conditions and when compared with inactive controls, (7 RCT and 1 randomized crossover controlled trial) although evidence for other cognitive domains remains inconclusive (Li et al., 2025).

A far as population suffering from cardiopulmonary diseases, in 4 RCTs, NW-based programs in patients with chronic heart failure and low ejection fraction have demonstrated meaningful gains in exercise tolerance and peak oxygen uptake, alongside better performance in field tests such as the six-minute walk test (Dhamayanti et al., 2025), and in individuals with chronic respiratory diseases (12 clinical studies), NW improves functional capacity and reduces dyspnea, with additional benefits on fatigue and disease-specific quality of life (Vilanova-Pereira et al., 2025). Finally, in populations characterized by chronic pain and fatigue, 14 RCTs have reported that NW has been able to reduce symptom intensity and enhance functional status and perceived health (González-Devesa et al., 2024).

Overall, these findings describe NW as a versatile intervention capable of producing clinically relevant improvements in physical fitness, symptom burden, and quality of life across a wide range of health conditions, and, although most studies still emphasize the need for larger and methodologically stronger trials, the available evidence supports considering NW as a safe and accessible whole-body modality that can be incorporated into exercise prescriptions to improve aerobic capacity, muscular fitness, and quality of life (Bullo et al., 2018).

Besides its effectiveness as a form of physical exercise, another strength of NW lies in its accessibility and social utility. The technique is perceived as easy to be learned and adapt to the practitioner's abilities, making it suitable for people of different ages and fitness levels (Anna Zurawik, 2020). Moreover, it does not require expensive or complex equipment and can be practiced mainly outdoors in both urban and natural environments. Indeed, practicing a nature sport throughout the season promotes socialization among participants and elevates perceived well-being (Raça et al., 2023). Furthermore, sociological research indicates that the values most frequently associated with the NW are in the personal and psychosocial/psychophysiological domains. This underscores that NW is a multidisciplinary practice whose benefits extend beyond motor performance or mere contact with nature (Szymczak et al., 2024, 2025).

In addition, NW also has a competitive side, featuring speed races and regularity events where pacing and technique are judged under standardized rules. Competitions run year-round all over the world, organized by clubs, national federations, and international circuits, and range from chip-timed time trials to mass-start races on road, track, and trail. These events attract participants of all ages and skill levels, fostering whole community engagement with this activity (Maas et al., 2023).

In conclusion, the literature on NW has progressed from early physiological studies that confirmed its specific metabolic and cardiovascular profile, to more detailed biomechanical analyses of technique, and subsequently to clinical and rehabilitative applications.

However, as discussed in the dedicated chapter, many of these benefits appear to depend on an appropriate technique, and there remains a need for tools that can quantify the quality of technical execution, particularly in real-world settings rather than the laboratory. In this context that recent attempts to integrate technology into NW practice have emerged, particularly in projects involving sensor-equipped poles.

1.6 Wearable & Technologies for Health: the Next Phase in Nordic Walking

Setting aside the specific context of NW for a moment, research on wearable technologies has increased markedly in recent years (Hedley et al., 2010; Seshadri et al., 2019a, 2019b), a trend analogous to what has been observed for NW. In recent years, digital devices have revolutionized the way physical activity is observed, measured, and interpreted, enabling the application of advanced analytical tools beyond research laboratories (Adesida et al., 2019; Düking et al., 2021). Devices such as smartwatches, inertial sensors, accelerometers, and physiological monitoring systems are now widely used to record variables related to performance, movement, and cardiovascular responses (Aroganam et al., 2019; Halson, 2014). Recent studies show that these tools enable a more objective and continuous assessment of exercise, improving intensity control, safety, and the personalization of training programs (Assaad et al., 2025; Seshadri et al., 2019a, 2019b). In clinical and rehabilitative contexts, adoption of wearables is also growing **(Fig.8)**, alongside their use in large-scale, population-based studies (Henriksen et al., 2018; Huhn et al., 2022).

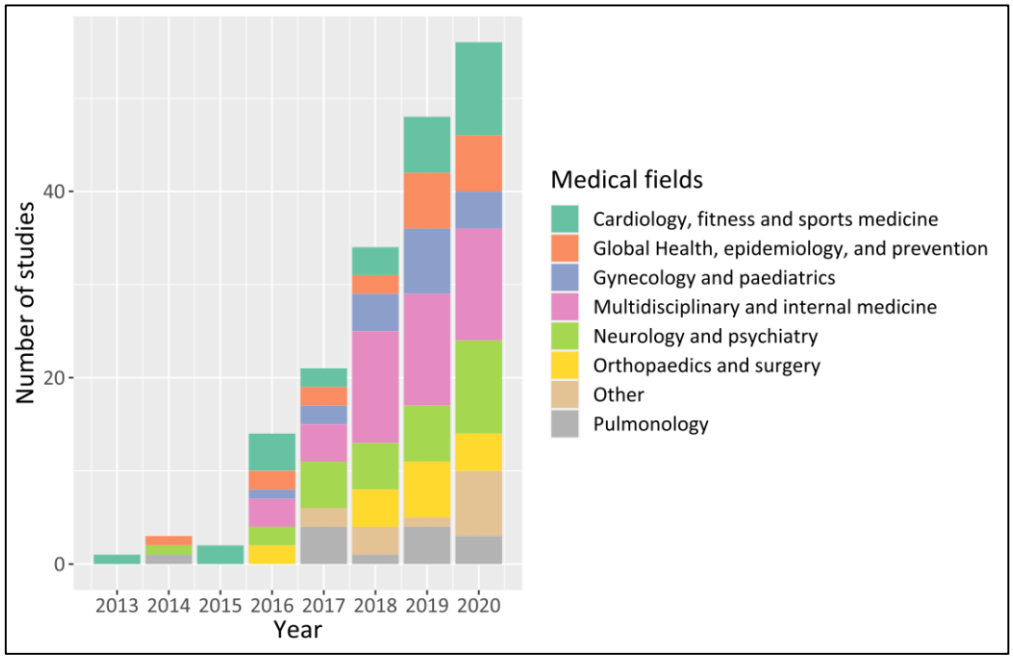

Fig. 8. Studies per medical field. *Reproduced from Huhn et al. (2022) "The impact of wearable technologies in health research: scoping review", JMIR mHealth and uHealth.*

Research on wearable technologies has facilitated remotely monitored exercise protocols, opening new perspectives for health promotion and disease prevention (Haberlin et al., 2018; Di Blasio et al., 2021, 2022; Duregon et al., 2022). Wearable sensors and monitoring systems have enabled a more dynamic, personalized approach to exercise prescription, extending physiological assessment beyond the laboratory and into real-world environments; nevertheless, many studies still call for further work to standardize protocols, verify and improve measurement accuracy, and clarify sport-specific effects and best-practice guidelines for implementation (Düking et al., 2020; Fuller et al., 2020; Shcherbina et al., 2017).

Returning to the focus of this thesis, NW has also evolved in response to this technological shift. Beyond monitoring traditional physiological parameters, research interest is increasingly turning to the only indispensable tool in NW: the pole. The aim is to analyze technique and movement quality with greater precision. This shift moves beyond physiological responses to target the mechanical and coordinative components of movement by integrating sensors into the poles themselves.

1.7 Nordic Walking and Sensorized Poles: What Do We Know?

In recent years, the drive to integrate technology into NW practice has led to the development of several prototypes of sensorized poles (Huta-Osiecka et al., 2022; Marciniak et al., 2021a; Wudarczyk et al., 2023). These devices represent an evolution of traditional equipment through the integration of sensors and electronic components. Their primary goal is to provide an objective measurement of the NW practice, as seen in the study by Krejčí et al., (2013), where poles were used to measure the force during NW activity, which is a line of research derived from similar works on cross-country skiing (Hentschel et al., 2021; Steinbild et al., 2020). Currently, most of these projects are developed within academic and laboratory settings. The most commonly integrated sensors include accelerometers, gyroscopes, and force and pressure sensors (Mocera et al., 2018; Pierleoni et al., 2022; Szpala et al., 2023). Despite the growing number of studies and prototypes, the dissemination of sensorized poles beyond research labs remains very limited. In most cases, these devices are used as experimental measurement tools to validate movement analysis models or to study the impact of the NW on particular health conditions in controlled environments (Wochna et al., 2022). They are often complex, custom setups created for individual studies, requiring dedicated equipment, specific calibrations, and technical expertise that are not yet compatible with large-scale use or everyday practice. Another barrier to broader application is the lack of standardization; each research group tends to adopt different configurations and sensors, making it difficult to compare results directly or to establish shared evaluation parameters. Finally, there is also a shortage of studies evaluating walkers' subjective perceptions across different pole types. To date, research is available only on the usage of different pole lengths (E. A. Hansen & Smith, 2009). Nevertheless, the potential of sensorized poles is clear. Objective data acquisition during NW could represent a significant step toward precise quantification of the technique, with important implications in both scientific and applied domains.

As we have seen, deviations from the correct technique have been shown to lead to modifications in physiological and biomechanical responses (Pellegrini et al., 2018); for this reason, a tool capable of automatically evaluating technical correctness can be an important ally to both instructors and practitioners. (Pellegrini et al., 2022; Wudarczyk et al., 2023).

1.8 General Aims of This Doctoral Project

The potential gap in the literature, as outlined in the previous section, serves as the starting point of this doctoral thesis. On one side, there is a shortage of studies specifically aimed at exploring users' subjective perceptions when using different NW pole types; on the other, there is the limited integration and underdevelopment of technologies, readily available on the market and not exclusively intended for experimental setups, that are capable of qualitatively and quantitatively monitoring the biomechanical parameters of NW practice and supporting movement professionals in the assessment, prescription, and monitoring of NW training. In this framework, there is a need for commercial tools that move beyond traditional indicators of physiological effort, such as heart rate monitors. Another aim is to broaden the understanding of the effects of NW on balance, strength, and flexibility across different populations.

To fulfill this goal, Gabel S.r.l. co-funded the doctoral project to better develop an instrumented NW pole called E-Poles (*E-Poles – Digital poles*, s.d.), accompanied by a dedicated mobile application and web portal.
This system consists of a pair of poles, with electronics completely integrated in the handle of the sticks, capable of acquiring, processing, and managing a wide range of biomechanical parameters detectable during NW, thus providing detailed information on technical execution. The associated digital platform also enables the monitoring of progress over time, the analysis of data in an integrated manner, and the provision of immediate feedback, facilitating the optimization of practice and the adoption of personalized interventions.

In the first line of investigation, conducted in a group of healthy NW practitioners, the aim was to identify, if present, a pole type that yields superior biomechanical and physiological responses, to be carried forward in future projects.

Then, for the main line of research, we tested the E-Poles system by integrating it into a structured, real-world NW learning program involving two populations: healthy women (HW) and breast cancer survivors (BCS). The primary aim was to assess the feasibility and performance of the instrumented poles and digital platform under real-world conditions, where feedback was provided exclusively based on the data recorded by the poles, and also to evaluate the effectiveness of a standard teaching format of NW. As a secondary objective, we explored potential differences in the progression and learning of the NW technique between the two populations. To our knowledge, no previous studies have implemented such a structured NW learning program using instrumented poles and an integrated digital platform in real-world conditions, providing feedback only from pole-derived data. BCS were included because they represent a clinically relevant group for whom NW is already proposed as a feasible and accessible form of exercise, as outlined in the section on NW in health research.

This was made possible through the collaboration with the University “Gabriele d’Annunzio” of Chieti-Pescara and the Integrated Medicine Ambulatory of the “G. Bernabeo Hospital” in Ortona (Italy), where part of the doctoral activity was carried out, and thanks to the supervision of Professor Andrea Di Blasio.

In parallel, this thesis also aims to extend the knowledge about the effects of NW on balance, strength, and flexibility in the two cited populations. Accordingly, this doctoral thesis presents and discusses the results of two distinct data collections, organized into three separate studies.
A further scientific task undertaken within the doctoral project was to provide the company with scientific consulting and information for the development of the app and to enrich the returned parameters with evidence-based content.

The first study focuses exclusively on walkers' responses and subjective perceptions. The second study develops and applies a biomechanical assessment protocol using commercial instrumentation in the populations of HW and BCS, while the third evaluates the effects of NW on balance, strength, and flexibility in both cohorts.

To be more specific, **Study 1**, titled "Muscular engagement, metabolic responses and subjective perception with different types of Nordic walking poles," aims to deeply understand the effects and the perception of three different pole types.

Study 2, titled "Learning Nordic Walking Technique with Sensorized Poles and Automated Feedback in Breast Cancer Survivors and Healthy Women: A Pilot Comparative Study" aims to assess if the use of the E-pole can influence the learning of the NW technique.

Finally, **Study 3**, conducted concurrently with Study 2 and titled "Effects of an 8-week Nordic Walking program on functional capacity, balance, and flexibility in breast cancer survivors and healthy women" seeks to expand knowledge on the use of NW within a health-oriented exercise program.

2 STUDY 1 – MUSCULAR ENGAGEMENT, METABOLIC RESPONSES AND SUBJECTIVE PERCEPTION WITH DIFFERENT TYPES OF NORDIC WALKING POLES.

Abstract

Purpose: The literature already demonstrates the need for the correct Nordic Walking (NW) style to maximize the positive effects of this activity. But what happens with different kinds of poles? This study aims to evaluate the differences in muscle activation and subjective perception of usage while walking with three different types of poles at different speeds.

Methods: 12 NW practitioners walked on a treadmill at 3.5 and 5 $km \cdot h^{-1}$ with 3 different poles: a classic NW pole (NWP), a pole with a wheel at the bottom that can rotate during the contact phase and locks during the recovery phase (WP), and the previous pole with a T-shaped handle (TWP). Metabolic parameters were recorded during the last minute of the 3.5 $km \cdot h^{-1}$ walk. At both velocities, kinematic measurements of body and pole movement with a motion capture system and EMG signals of 8 muscles (Erector Spinae (ES), Latissimus Dorsi (LD), Anterior Deltoid (AD), Posterior Deltoid (PD), Biceps Brachii (BB), Triceps Brachii (TB), Flexor Carpi Radialis (FCR), and Extensor carpi radialis (ECR)) using surface EMG were recorded. RMS values were calculated for the pushing and pole recovery phases. At the end of each 5-minute walking bout, each participant was given a questionnaire (visual analogue scale 0-100) about the subjective perception of the pole usage with four items: comfort of the handle (HC), push effectiveness (PE), comfort on the recovery (PR), and ease of pole handling (PH). A two-way ANOVA for repeated measures was used to assess the effect of pole type and speed.

Results: No effect of pole type was found in the metabolic parameters. Regarding subjective perception, for comfort of the handle, push effectiveness, and ease of pole handling, regardless of velocity, the NWP has yielded better results on the other poles ($P < 0.05$, $P < 0.05$, and $P < 0.01$, respectively). Regarding the comfort of recovery, the NWP yields better results only on the TWP ($P = 0.013$). In the muscular activation, muscle activity was found to increase with speed for all investigated muscles and phases ($P<0.05$), with no effect of pole type ($p>0.05$).

Significant differences emerged between the classic NW pole and the other two types ($P < .001$), regardless of velocity, resulting in a decrease in the shoulder's range of motion. This is also reflected in the shorter contact time for the TWP when compared with the NWP ($P = .007$) at any speed.

Conclusions: Based on these results, there are indications that using the classic NW poles could be better not only for subjective perception but also because poles with wheels may distance the user too much from the correct NW technique.

2.1 Introduction

Nordic Walking (NW) is an increasingly adopted form of physical activity that integrates the use of poles into conventional walking. By promoting active involvement of the upper limbs and trunk, NW has been shown to increase overall exercise intensity compared to regular walking (Pellegrini et al., 2017). For this reason, NW has gained increasing application in health-related contexts over the past years, where it has been proposed as a safe and effective intervention for improving cardiorespiratory fitness, muscular strength, and functional mobility (Skórkowska-Telichowska et al., 2016; Nagyova et al., 2020; Morano et al., 2024). Beyond enhancing cardiovascular load, NW also contributes to a more balanced distribution of muscular effort between the upper and lower body, reduces joint load, and improves postural stability. Despite these benefits, the literature has also emphasized that the physiological and biomechanical advantages of the NW technique are strongly dependent on its correct execution (Pellegrini et al., 2018). Inefficient pole uses or wrong movement patterns may limit upper limb contribution, compromise energy transfer, and consequently attenuate the positive outcomes. In parallel with the growing diffusion of NW, manufacturers have progressively introduced a variety of pole designs (Gabel, Leki, Fizan, etc.). These differ in grip ergonomics, strap systems, length adjustability, and mechanical characteristics such as stiffness and weight distribution. More recently, poles have also been equipped with integrated technologies, especially for research set-up, including sensors and feedback systems, aimed at monitoring movement quality and physiological responses (Pellegrini et al., 2022; Huta-Osiecka et al., 2022; Marciniak et al., 2021b; Wudarczyk et al., 2023). Such diversity raises the question of whether pole design itself may influence not only subjective comfort and usability, but also muscular engagement, metabolic cost, and perceived exertion during walking.

To date, no studies have investigated how specific pole characteristics affect the

physiological and biomechanical aspects of NW. Existing research has mainly examined variations in pole length (E. A. Hansen & Smith, 2009).

In this context, some manufacturers are attempting to introduce alternative pole designs that differ from the traditional configuration, including wheel-based mechanisms intended to provide a different type of support and potentially modify the pole's interaction with the ground. These systems were originally designed to provide a different form of mechanical support during movement, reduce pole lifting during the gait cycle, and potentially enhance balance by maintaining an additional point of support throughout walking. Such design choices suggest that they could influence the coordination of the gesture and, consequently, some biomechanical or perceptual aspects of Nordic Walking. In this gap, the primary focus of this work is to investigate whether equipment design can influence muscular activation, metabolic demand, and subjective perception. This study aims to experimentally evaluate, under controlled laboratory conditions, the influence of three different pole designs on joint kinematics, muscular activation, metabolic demand, and subjective perception during Nordic Walking.

2.2 Materials And Methods

2.2.1 Subjects

Twelve adults (7 females, 5 males; mean ± SD: age 34.8 ± 12.3 years) voluntarily participated in this study. All participants had at least one year of experience in Nordic Walking (NW) using the INWA technique (Maas et al., 2023) and reported regular practice. Inclusion criteria required the absence of musculoskeletal, neurological, or cardiovascular disorders that could affect walking or pole handling. Participants were from moderately to highly active backgrounds, as indicated by their self-reported physical activity levels.

2.2.2 Study Design

Each participant completed six walking trials on a treadmill (RL3500E; Rodby, Vänge, Sweden) with a belt surface of 2.5 m × 3.5 m. The trials were performed at two walking velocities, 3.5 km·h^{-1} and 5 km·h^{-1}, with three different pole types (**Fig. 1**):

1. **NWP (Classic Nordic Walking Pole)** – standard design with ergonomic handgrip and traditional strap;
2. **WP (Wheel Pole)** – similar shaft and handgrip but equipped with a rotating wheel at the tip that rolls during the swing phase and locks during push-off. This modification was made to allow users to bring the pole forward during the recovery phase without having to lift it, as is typically required with a traditional pole.
3. **TWP (T-handle Wheel Pole)** – identical to WP but featuring a horizontal T-shaped handle.

Fig. 1, The three types of poles, from left to right: the Classic Nordic Walking pole (**NWP**), the Wheel Pole (**WP**), and the T-handle Wheel Pole (**TWP**).

The order of pole and speed conditions was randomized across participants to minimize fatigue effects. Before data collection, all subjects completed a familiarization session to practice walking on the treadmill and using the three different pole designs. The pole length was individually adjusted to 68% of body height, in accordance with standard NW recommendations. Each trial lasted 5 minutes, with a 3-minute rest between conditions. Participants were instructed to maintain a natural NW technique and avoid excessive arm movement or compensation. Energy demand was analyzed during the 3.5 $km \cdot h^{-1}$ trial, while kinematic data and muscle activation were recorded at both 3.5 $km \cdot h^{-1}$ and 5 $km \cdot h^{-1}$.

2.2.3 Measurements

Gas exchange and ventilatory parameters were collected breath-by-breath during the entire 5-minute trial using a metabolic cart (Quark CPET; Cosmed, Rome, Italy). The gas analyzers and flowmeter were calibrated before each session using standard reference gases and a 3-L volume syringe, respectively.

Joint and pole kinematics were recorded using a 6-camera motion capture system (MCU240, ProReflex; Qualisys, Gothenburg, Sweden) operating at 100 Hz. Reflective hemispheric markers were positioned bilaterally on the glenohumeral joint, lateral humeral condyle, dorsal wrist, greater trochanter, lateral femoral condyle, lateral malleolus, and fifth metatarsal phalangeal joint. Two reflective markers were attached to each pole, one 40 cm from the top and one 40 cm above the tip.

Surface EMG signals were recorded from eight muscles: Erector Spinae (ES), Latissimus Dorsi (LD), Anterior Deltoid (AD), Posterior Deltoid (PD), Biceps Brachii (BB), Triceps Brachii (TB), Flexor Carpi Radialis (FCR), and Extensor Carpi Radialis (ECR), using a wireless system (OT Bioelettronica, Turin, Italy). Disposable electrodes were placed according to SENIAM guidelines after standard skin preparation (Hermens et al., 2000).

Kinematic and EMG data were acquired synchronously, thanks to a trigger signal sent from the camera motion system to the EMG auxiliary input channel, for 30 s during the last minute of each trial.

Immediately after each 5-minute trial, participants completed a visual analog scale (VAS, 0–100) to evaluate four perceptual dimensions: comfort of handle (HC), push effectiveness (PE), comfort during recovery (PR), and ease of pole handling (PH). Participants rated each item based on their overall impression during the trial, where "0" represented the worst results and "100" represented the best results.

2.2.4 Data Analysis

Metabolic expenditure was determined from oxygen uptake (VO_2) data averaged over the last minute of each trial. Kinematic data were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency determined by residual analysis (Pellegrini et al., 2017). For the kinematic and electromyographic data analysis, gait cycles and the poling phase were identified for all conditions from the displacement of the right wrist and pole. The poling phase was defined as beginning at the time point when the marker on the right wrist reached its maximal forward position along the horizontal axis. The end of the poling phase was identified as the time when the poles started to move forward. Cycle time (CT) was therefore calculated as the time between two consecutive beginnings of the poling phase, and the duration of the poling phase was defined as the interval between the beginning and the end. The duration of the recovery phase was then calculated as the difference between the cycle duration and the poling phase duration. Flexion-extension movements have been calculated for the elbow and shoulder on the sagittal plane. Angular range of movement (ROM) values for each joint were calculated for a minimum of 15 cycles and then averaged. Raw EMG signals were band-pass filtered (bi-directional, 4th-order, zero-lag Butterworth, bandwidth: 20 ± 400 Hz). All EMG signals were then rectified, and the RMS value was obtained by an overlapping moving window with a length of 125 ms and an overlap of 1 point.

The RMS value of the EMG signal for each condition was normalized to the maximum voluntary contraction (MVC) recorded for each muscle. The EMG value curves were visually inspected by overlaying all cycles in a single graph, and any cycles showing clear artifacts were excluded from the analysis.

Muscle engagement was then estimated by calculating the average RMS value over the entire cycle duration, over the poling phase, and over the recovery phase. Data from at least 15 cycles were used and averaged.

Kinematic and electromyographic data were processed using MATLAB R2020b (MathWorks Inc., Natick, MA, USA) and Excel 2003 (Microsoft Corporation, Redmond, Washington, USA).

2.2.5 Statistical Analysis

Data distribution was assessed using the Shapiro–Wilk test. In case of non-normal distribution, non-parametric tests were considered. A 2 (velocity [$km \cdot h^{-1}$]: 3.5 vs 5) × 3 (poles: NWP vs WP vs TWP) repeated measures ANOVA was performed to evaluate changes in every measure. When significant effects were detected, post-hoc analyses were conducted using Bonferroni correction to adjust for multiple comparisons. Effect sizes are reported as partial eta squared (η^2) for key findings. The level of statistical significance was set at $p < 0.05$. All statistical analyses were performed using JASP software, version 0.18 (JASP Team, Amsterdam, Netherlands).

2.3 Results

The repeated-measures ANOVA did not reveal any significant differences (all $p>0.05$) in metabolic cost among the three pole types at 3.5 $km \cdot h^{-1}$ **(Fig. 2).**

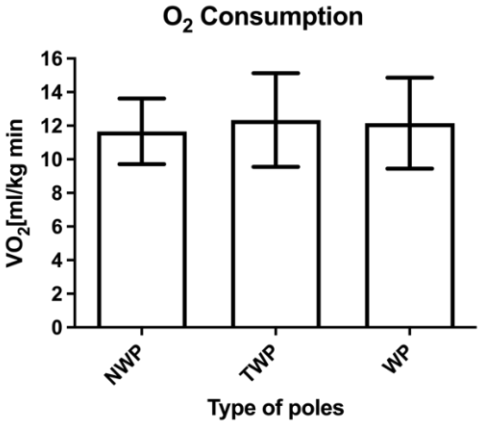

Fig.2: Mean values of VO_2. The error bars indicate standard deviation.

Cycle duration **(Table 1)** was influenced by pole type ($F(2,16) = 6.84$, $p = 0.007$) and walking speed ($F(1,8) = 259.47$, $p < 0.001$), with no pole type × speed interaction. Post-hoc comparisons averaged across speeds showed shorter cycle duration with TWP compared with NWP ($p = 0.035$) and WP ($p = 0.035$), while NWP and WP did not differ ($p = 0.299$).

Pole contact time was not affected by pole type, whereas walking speed showed a significant main effect ($F(1,8) = 6.70$, $p = 0.032$); the pole type × speed interaction was not significant, similarly to the recovery time who was not influenced by pole type and no pole type × speed interaction was detected, while walking speed had a significant main effect ($F(1,8) = 6.44$, $p = 0.035$).

Recovery time was not influenced by pole type, and no pole type × speed interaction was detected, while walking speed had a significant main effect ($F(1,8) = 6.44$, $p = 0.035$).

Table 1: Mean ± SD of cycle duration, pole contact time, and recovery time for the three pole types. Bold values indicate statistically significant effects ($p < 0.05$). Post-hoc tests of the pole type showed shorter cycle duration with TWP compared with NWP and WP (both $p = \mathbf{0.035}$), whereas NWP and WP did not differ ($p = \mathbf{0.299}$)

	NWP 3.5 km·h⁻¹	**NWP** 5 km·h⁻¹	**WP** 3.5 km·h⁻¹	**WP** 5 km·h⁻¹	**TWP** 3.5 km·h⁻¹	**TWP** 5 km·h⁻¹	**Speed (F), p**	**Pole type (F), p**	**Interaction (F), p**
Cycle time (s)	1.397 ± 0.104	1.160 ± 0.079	1.372 ± 0.102	1.158 ± 0.071	1.326 ± 0.107	1.147 ± 0.078	(259.4), 0.001	(6.84), 0.007	(3.06), 0.075
Pole Contact Time (s)	0.927 ± 0.081	0.722 ± 0.057	0.752 ± 0.450	0.714 ± 0.055	0.866 ± 0.090	0.697 ± 0.064	(6.70), 0.032	(1.09), 0.361	(1.00), 0.391
Recovery Time (s)	0.628 ± 0.377	0.463 ± 0.384	0.618 ± 0.094	0.470 ± 0.049	0.589 ± 0.106	0.326 ± 0.375	(6.44), 0.035	(0.61), 0.553	(0.23), 0.798

A significant main effect of pole type emerged for shoulder ROM **(Fig. 3)** ($F(2,16) = 49.22$, $p < 0.001$), whereas neither speed nor the interaction between the two factors reached significance. ROM. The elbow ROM did not show significant effects of pole type (all $p > 0.05$).

Regarding EMG activity, no significant main effects of pole type were found for any muscle in either the contact or recovery phases. Walking speed, instead, produced changes in activation.

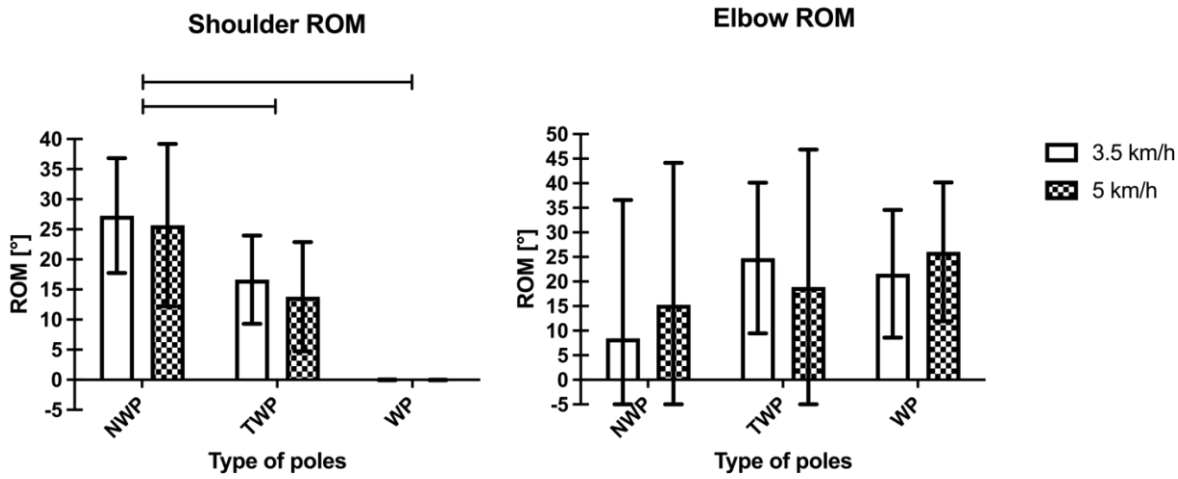

Fig.3. Shoulder and Elbow ROM across the three poles at both walking speeds. The error bars indicate standard deviation. Horizontal bars indicate significant differences.

During the contact phase, EMG amplitude **(Table 2)** was higher at 5 km·h^{-1} in the Latissimus Dorsi ($F(1,8) = 21.57$, $p = 0.002$), Biceps Brachii ($F(1,8) = 7.29$, $p = 0.027$), and Anterior Deltoid ($F(1,8) = 7.11$, $p = 0.029$). No significant effects of speed were detected for the Posterior Deltoid, Triceps Brachii, Flexor Carpi Radialis, or Extensor Carpi Radialis (all $p > 0.05$).

During the recovery phase **(Table 3)**, higher speed resulted in increased activation of the Erector Spinae ($F(1,8) = 6.71$, $p = 0.032$), Latissimus Dorsi ($F(1,8) = 7.92$, $p = 0.023$), Posterior Deltoid ($F(1,8) = 7.29$, $p = 0.027$), and Triceps Brachii ($F(1,8) = 8.92$, $p = 0.017$). The Anterior Deltoid showed a trend toward higher activation at 5 km·h^{-1} ($F(1,8) = 5.15$, $p = 0.053$), while the Biceps Brachii, Flexor Carpi Radialis, and Extensor Carpi Radialis did not vary significantly with speed in this phase (all $p > 0.05$). A significant pole × speed interaction was found only for the Erector Spinae during the contact phase ($F(2,16) = 5.02$, $p = 0.020$). The increase in activation from 3.5 to 5 km·h^{-1} was greater when using the wheel-based poles (WP and TWP), but the post hoc comparisons between individual pole–speed combinations did not show any difference (all $p > 0.05$).

Table 2: Mean ± SD of EMG normalized to MVC during the pole **contact phase**. No significant post hoc differences were found for Erector Spinae (all p>0.05).

	NWP 3.5 km·h⁻¹	**NWP** 5 km·h⁻¹	**WP** 3.5 km·h⁻¹	**WP** 5 km·h⁻¹	**TWP** 3.5 km·h⁻¹	**TWP** 5 km·h⁻¹	**Speed (F), p**	**Pole type (F), p**	**Interaction (F), p**
Muscle									
Erector Spinae	0.119 ± 0.05	0.055 ± 0.03	0.087 ± 0.08	0.078 ± 0.05	0.095 ± 0.10	0.078 ± 0.05	(2.895), 0.127	(0.057), 0.945	(5.015), 0.020
Latissimus Dorsi	0.065 ± 0.06	0.096 ± 0.09	0.069 ± 0.06	0.080 ± 0.05	0.066 ± 0.06	0.091 ± 0.07	(21.569), 0.002	(0.161), 0.853	(0.396), 0.680
Anterior Deltoid	0.055 ± 0.04	0.098 ± 0.05	0.078 ± 0.07	0.131 ± 0.13	0.052 ± 0.03	0.075 ± 0.05	(7.110), 0.029	(0.949), 0.408	(0.468), 0.635
Posterior Deltoid	0.097 ± 0.05	0.115 ± 0.05	0.094 ± 0.07	0.080 ± 0.08	0.073 ± 0.04	0.143 ± 0.16	(1.318), 0.284	(0.414), 0.668	(1.690), 0.216
Biceps Brachii	0.077 ± 0.07	0.113 ± 0.10	0.091 ± 0.07	0.137 ± 0.12	0.078 ± 0.07	0.079 ± 0.07	(7.285), 0.027	(3.478), 0.056	(1.711), 0.212
Triceps Brachii	0.110 ± 0.12	0.130 ± 0.14	0.096 ± 0.14	0.104 ± 0.17	0.081 ± 0.07	0.133 ± 0.16	(3.808), 0.087	(0.380), 0.690	(1.254), 0.312
Extensor Carpi Radialis	0.067 ± 0.04	0.080 ± 0.05	0.064 ± 0.04	0.081 ± 0.05	0.070 ± 0.04	0.085 ± 0.06	(9.574), 0.017	(1.387), 0.282	(0.084), 0.920
Flexor Carpi Radialis	0.051 ± 0.03	0.073 ± 0.04	0.054 ± 0.03	0.083 ± 0.06	0.053 ± 0.04	0.073 ± 0.05	(4.876), 0.063	(1.366), 0.287	(3.434), 0.061

Table 3: Mean ± SD of EMG normalized to MVC during the pole **recovery phase**.

	NWP 3.5 km·h⁻¹	**NWP** 5 km·h⁻¹	**WP** 3.5 km·h⁻¹	**WP** 5 km·h⁻¹	**TWP** 3.5 km·h⁻¹	**TWP** 5 km·h⁻¹	**Speed (F), p**	**Pole type (F), p**	**Interaction (F), p**
Muscles									
Erector Spinae	0.072 ± 0.079	0.098 ± 0.088	0.079 ± 0.085	0.131 ± 0.111	0.092 ± 0.098	0.098 ± 0.056	(6.712), 0.032	(1.233), 0.318	(1.571), 0.238
Latissimus Dorsi	0.039 ± 0.031	0.076 ± 0.077	0.043 ± 0.026	0.070 ± 0.040	0.051 ± 0.034	0.081 ± 0.053	(7.924), 0.023	(0.516), 0.606	(0.134), 0.876
Anterior Deltoid	0.032 ± 0.018	0.053 ± 0.033	0.078 ± 0.074	0.139 ± 0.204	0.041 ± 0.020	0.076 ± 0.049	(7.292), 0.027	(1.927), 0.178	(0.311), 0.737
Posterior Deltoid	0.038 ± 0.024	0.060 ± 0.035	0.066 ± 0.052	0.096 ± 0.068	0.054 ± 0.038	0.096 ± 0.091	(5.154), 0.053	(1.665), 0.220	(0.466), 0.636
Biceps Brachii	0.036 ± 0.025	0.053 ± 0.037	0.037 ± 0.028	0.055 ± 0.044	0.037 ± 0.026	0.053 ± 0.046	(3.941), 0.082	(0.880), 0.434	(0.200), 0.821
Triceps Brachii	0.037 ± 0.029	0.055 ± 0.041	0.041 ± 0.043	0.076 ± 0.079	0.043 ± 0.028	0.08 ± 0.069	(8.918), 0.017	(1.738), 0.207	(1.121), 0.350
Extensor Carpi Radialis	0.046 ± 0.030	0.072 ± 0.051	0.049 ± 0.033	0.074 ± 0.058	0.051 ± 0.033	0.079 ± 0.054	(7.654), 0.024	(0.245), 0.786	(1.681), 0.217
Flexor Carpi Radialis	0.039 ± 0.026	0.061 ± 0.040	0.041 ± 0.028	0.065 ± 0.051	0.041 ± 0.030	0.064 ± 0.044	(25.321), 0.001	(1.968), 0.172	(0.343), 0.714

Significant main effects of both walking speed and pole type were found for PE, HC, and PR **(Fig.4)**, whereas PH was significantly affected only by pole type. For PE, higher values were reported at 5 km·h^{-1} compared with 3.5 km·h^{-1} ($p = 0.004$). The classic NWP was perceived as providing greater push effectiveness than both WP and TWP ($p = 0.008$). Regarding HC, both speed ($p = 0.015$) and pole type ($p < 0.001$) influenced perception. Participants rated the NWP as markedly more comfortable than WP and TWP (both $p < 0.001$), with slightly higher scores at the faster pace.

For PR, significant effects of speed ($p = 0.026$), pole type ($p = 0.013$), and their interaction ($p = 0.031$) were found. The NWP was associated with better recovery perception, particularly at 5 km·h^{-1}.

Finally, PH differed significantly across pole types ($p < 0.001$), with the NWP perceived as substantially easier to handle than both WP and TWP, which showed comparable and lower scores.

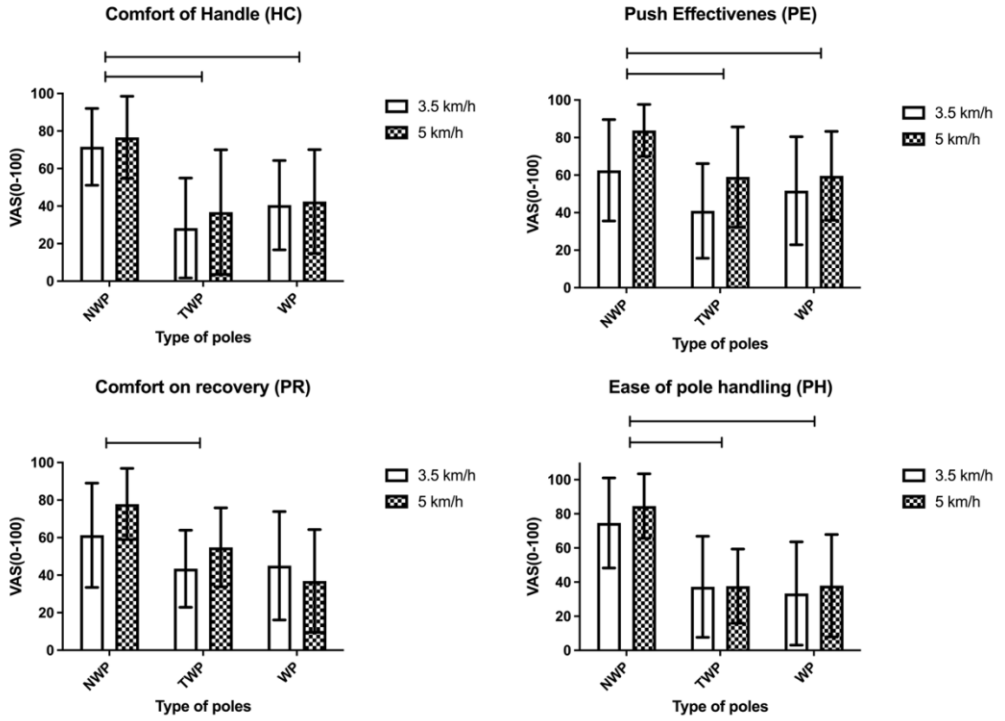

Fig. 4. Mean values for the VAS ratings (0–100) for HC, PE, PR, and PH for each pole type. The error bars indicate standard deviation. Horizontal bars indicate significant differences.

2.4 Discussion

The primary aim of this study was to determine whether three different NW pole designs elicited distinct biomechanical, physiological, or perceived effects. To our knowledge, no previous studies have systematically compared different NW pole designs within the same experimental framework. Most available research has compared NW with conventional walking or examined variations in technique (Dziuba et al., 2015; Pellegrini et al., 2015, 2017) or has measured the effect of differences in pole lengths (E. A. Hansen & Smith, 2009) rather than investigating how different pole designs may influence the execution of the movement. Overall, the results suggest that the structural modifications introduced by adding the wheel to the tip of the poles or by changing the inclination of the handle did not substantially alter the energetic or neuromuscular demands of walking at the tested speeds.

Specifically, metabolic cost at 3.5 $km \cdot h^{-1}$ remained comparable across the three poles, and the absence of significant differences may reflect the relatively low walking intensity. The small, non-significant increases observed for both WP and TWP may be related to subtle coordination adjustments or to the additional attentional demands required when managing a non-traditional pole requiring a different pattern.

Walking speed was the main determinant of temporal parameters: increasing speed from 3.5 to 5 $km \cdot h^{-1}$ consistently shortened cycle duration, pole contact time, and recovery time across all pole types. This indicates a global compression of the NW timing pattern at higher speeds, with participants maintaining the same coordination strategy while executing the gesture faster. Pole design played a secondary role, affecting only the overall cycle duration (TWP showing a slightly shorter cycle than NWP and WP); meanwhile, pole contact and recovery times were primarily driven by walking speed and did not show a specific main effect of pole type when considered as absolute phase durations. The absence of a pole type × speed interaction further supports that speed-related adjustments operate similarly regardless of pole design.

Moving on to the kinematic analysis, the shoulder range of motion (ROM) differed markedly across pole designs. NWP showed the greatest shoulder ROM, and WP exhibited smaller shoulder ROM. In contrast, TWP showed an almost null shoulder ROM at both speeds, indicating a substantial restriction of shoulder movement. Elbow ROM did not vary across pole types or speed, suggesting that participants maintained a similar flexion–extension pattern regardless of the equipment used.

Within this framework, the longer cycle observed with NWP may reflect the larger shoulder range of motion allowed by this design, which could require marginally more time for the whole contact–recovery sequence. Notably, the pattern observed with the NWP aligns with the technical features that the literature generally associates with the most effective execution of NW. (*INWA NORDIC WALKING*, s.d.; Pellegrini et al., 2018)

The EMG results provide further support for the limited impact of pole design on physiological load. Across all muscles and phases, activation patterns were mostly unaffected by the specific pole design used, and muscular activation tended to increase only at higher walking speeds, indicating that intensity probably had a greater influence than equipment characteristics. Participants' subjective perceptions provided the clearest distinctions between the three poles. Within our sample, these findings represent the participants' subjective impressions of using the three pole types. The NWP consistently received higher ratings for HC, PE, PR, and PH, indicating a generally more positive user experience. Walking speed also influenced these perceptions, with higher speeds tending to enhance the sensation of push and overall comfort across poles. However, the relative differences among NWP, WP, and TWP remained stable, suggesting that NWP was perceived as smoother and easier to manage, even as the intensity increased.

This study acknowledges a few limitations. Focusing on a single product line restricts the comparison and does not represent the full range of Nordic Walking poles currently available on the market. In addition, participants were more familiar with the classic NWP than with the wheel-based designs, which may have introduced a bias favoring the traditional pole in the perceptual measures and may also have influenced the naturalness and fluidity of the movement pattern during the trials.

2.5 Conclusion

In summary, the findings of this study provided useful indications for identifying which pole design may be more promising for future applications. Among the three tested models, the NWP was the one that best preserved the characteristic biomechanics of NW and was consistently perceived as more comfortable and easier to handle. Although physiological responses did not differ substantially across designs, the traditional pole offered the most natural movement pattern and the most favorable user experience. These results, therefore, offered valuable guidance to the company involved in the project, helping to determine which product may be most suitable to prioritize in future developments or research initiatives.

3 STUDY 2 – LEARNING NORDIC WALKING TECHNIQUE WITH SENSORIZED POLES AND AUTOMATED FEEDBACK IN BREAST CANCER SURVIVORS AND HEALTHY WOMEN: A PILOT COMPARATIVE STUDY

Abstract

Purpose: Growing literature furnishes evidence concerning the positive effects of Nordic Walking (NW) on health and disease. NW seems to positively affect the health of breast cancer survivors (BCS). Previous literature shows that a good technique is fundamental to secure and enhance its positive effects. To reach the best technical competence, both the number of introductory sessions and the efficacy of feedback are important. Therefore, this study aimed to observe the effect of a standard NW teaching format and that of sessions containing feedback based on a technological approach on the NW technique of BCS in both BCS and healthy women (HW).

Methods: Fifty-nine women took part in this pilot study: 30 BCS and 29 HW. All participants completed an initial cycle of eight INWA-based introductory NW lessons, twice per week. During the last lesson of this phase (T0), NW technique was recorded using sensorized E-Poles over a standardized 10-minute walk. Participants then completed a second cycle of eight NW sessions, again twice per week, and were allocated to either an E-Poles group (EP, receiving feedback based on sensor data from the previous session) or a standard-poles group (SP, receiving usual instructor feedback). At the end of this phase (T1), all participants repeated the standardized 10-minute test with E-Poles. Four E-Poles–derived indices were treated as primary outcomes: pole contact time (PCT), contact time symmetry (l/r_Ct), angle symmetry (l/r_inc), and left/right alternation regularity (l/r_alt). Grasp/cycle regularity (l/r_grasp) was also analyzed as an additional technique-related outcome. Outcomes were analyzed using generalized linear (mixed) models with the appropriate Beta or Gamma family. For l/r_alt, an aligned rank transform (ART) ANOVA was used when model assumptions were not met.

Results: For L/R contact symmetry (l/r_Ct) and L/R angle symmetry (l/r_inc), no significant main effects of cancer status or pole type (EP vs SP) and no cancer status × pole-type interactions were detected (all $p > .05$). Grasp/cycle regularity (l/r_grasp) similarly showed no significant effects or interactions. For L/R pace regularity (l/r_alt), the ART ANOVA showed a significant main effect of pole type

($p = 0.013$), with higher l/r_alt values in the EP condition. This difference was significant in HW ($p = 0.029$) and non-significant but directionally similar in BCS ($p = 0.193$). Within the EP condition, BCS showed lower l/r_alt values than HW ($p = 0.001$). In a longitudinal Beta model including time and lesson number, no significant interaction between cancer status and pole type was detected. Adherence to the second block of sessions (lessons 9–16) showed a significant main effect of pole type ($p < .001$), with higher adherence in the EP groups than in the SP groups. **Conclusions**: This pilot study suggests that a sensorized pole system providing automated, data-driven feedback can be feasibly integrated into supervised NW programs for both BCS and HW. Relying primarily on E-Poles–based feedback did not compromise temporal or angular symmetry or grip-regulation indices and was associated with selectively higher alternation regularity and greater adherence to the training program. An eight-lesson INWA-based introductory program appears sufficient to bring BCS and HW to broadly comparable levels of NW technique, although BCS may retain slightly lower alternation regularity. Larger studies with more heterogeneous protocols are needed to confirm these preliminary findings and to test the system in more autonomous or remote training settings.

3.1 Introduction

Nordic Walking (NW) is a type of physical exercise that includes the use of a specific pair of poles (Maas et al., 2023) and has gained increasing popularity in recent years, both as a discipline aimed at improving overall fitness and well-being in healthy individuals and as a non-pharmacological strategy to counteract the negative effects of major non-communicable chronic diseases that respond positively to physical exercise. One of the key features of NW is its active engagement of the upper limbs. This involvement of the upper body leads to a series of useful effects that can largely explain the recent surge in the popularity of NW. In particular, NW has been associated with higher oxygen consumption, while simultaneously resulting in a reduced perception of fatigue (Pellegrini et al., 2017; Sugiyama et al., 2013), favourable changes in body composition (Muollo et al., 2019; Sanchez-Lastra et al., 2020), and beneficial endocrine responses (Sanchez-Lastra et al., 2020). However, these benefits are not limited to metabolic and endocrine adaptations, as positive effects have also been reported in biomechanical (Roy et al., 2020), cardiovascular (Nagyova et al., 2020), pulmonary (Novotová et al., 2022), and other health-related domains (Skórkowska-Telichowska et al., 2016; Rodrigues et al., 2021).

In this context, NW is receiving growing attention for its potential benefits in breast cancer survivors (BCS), as it has been shown to increase upper-body and trunk strength (Malicka et al., 2011; Hanuszkiewicz et al., 2015, 2021), shoulder range of motion (Fischer, Krol-Warmerdam, Ranke, Vermeulen, Van der Heijden, et al., 2015), posture (Hanuszkiewicz et al., 2015, 2021), and aerobic fitness (Jönsson & Johansson, 2014), while also decreasing lymphedema(Jönsson & Johansson, 2009; Malicka et al., 2011; Di Blasio, Morano, Bucci, et al., 2016; Di Blasio, Morano, Napolitano, et al., 2016), pain, and depressive symptoms (Fields et al., 2016). If we also consider that, according to the literature, both pharmacological (e.g., chemotherapy) and non-pharmacological treatments for breast cancer are associated with a decline in daily physical activity and a rise in sedentary behavior (Agrawal, 2014; Wang & Woodruff, 2015; Fassier et al., 2016; De Groef et al.,

2018; Gal et al., 2019), NW appears to be a promising tool for preserving or enhancing the kinesiological health of BCS, with potential direct consequences for their overall psychophysical well-being. However, it is essential to consider two important aspects: first, the use of poles requires a specific NW technique; and second, the correct execution of this NW technique may be crucial to enhance the benefits associated with the practice, since t techniques different from INWA's style can lead to different and poorer biomechanical and physiological acute responses (Pellegrini et al., 2018). Consequently, it is also important to highlight that both the number of introductory lessons and the amount and quality of feedback provided are crucial to achieving a good NW technique.

These considerations highlight a current gap in the literature: the limited integration and development of commercially available technologies, not only designed for experimental setups, capable of qualitatively and quantitatively monitoring the biomechanical parameters of NW practice, beyond the more traditional indicators like metabolic load (Di Blasio et al., 2021; Düking et al., 2020) or sleep quality (Di Blasio et al., 2022).

A recent review (Huhn et al., 2022) highlighted how wearable technology is being increasingly adopted, over the last years, not only in sports contexts but also across a wide range, medical and clinical contexts, including cardiology, neurology, oncology, rehabilitation, and sports medicine, demonstrating not only its versatility but also its growing importance in evidence-based health interventions. An interesting feature of these devices can be the possibility of going beyond data collection: they can provide real-time (*Polar Team*, s.d.) or asynchronous remote feedback (Di Blasio et al., 2021, 2022), enabling more dynamic and responsive approaches to training, recovery, and long-term prevention. This allows the provision of continuous support, more personalized training plans, and easier access to effective movement-based programs even beyond traditional settings.

Furthermore, another essential aspect to explore is how technology can assist physical exercise professionals in their daily work by enabling accurate and continuous monitoring of the subject's physical activity.

Indeed, the use of technological devices in physical activity is becoming increasingly widespread and, in many cases, represents a natural evolution in how exercise is prescribed, monitored, and adapted over time. These tools may have the potential to bridge the gap between supervised and unsupervised sessions of NW (Hartvigsen et al., 2010), allowing for more consistent tracking of subject progress and behavior in real-world conditions.

In response to these challenges, various solutions are gradually emerging, including different types of electronic poles (Marciniak et al., 2021a; Pellegrini et al., 2022; Wudarczyk et al., 2023), designed with diverse technological approaches and equipped with various types of sensors. Those systems are capable of acquiring, managing, and analyzing a range of different parameters during NW sessions, thereby enabling detailed assessments of technique, movement, and forces. Those kinds of poles can offer a new opportunity for objective monitoring and personalized intervention in NW-based programs.

The primary objective of this pilot study is to assess the real-world applicability of a novel technology designed to support and enhance the NW technique within structured physical exercise programs. Specifically, the study aims to determine whether delivering a training program based primarily on feedback derived from data collected by the technology embedded in the poles can be an effective approach for enhancing technique and whether this system can assist professionals in their work. Finally, the study seeks to compare outcomes between a group of breast cancer survivors (BCS) and a group of age-matched healthy women (HW).

3.2 Materials and Methods

3.2.1 Subjects

The study enrolled 59 women divided into two groups. The first group included 30 BCS (mean age ± standard deviation: 56.6 ± 7.9 years). These participants were recruited from the Integrative Medicine Outpatient Clinic of ASL 02 Lanciano-Vasto-Chieti at the "G. Bernabeo" Hospital in Ortona and from the Department of Medicine and Aging Sciences at the University "G. D'Annunzio" of Chieti-Pescara. Inclusion criteria to participate in the intervention were medical eligibility to NW, a minimum of 6 months after breast cancer surgery. Exclusion criteria included current chemotherapy, current radiotherapy, and active diseases that could limit the ability to participate in NW, as well as prior participation in NW courses. The term "current" refers to the date of the baseline evaluation of each participant. Data were collected from January 2024 to May 2024. The local Ethics Committee approved this study (prot. #312/2015), and all the participants gave their written informed consent.

The second group of 29 HW (mean age ± standard deviation: 60 ± 9.13 years) was recruited at the CeRiSM – Research Center for Sport, Mountain and Health in Rovereto, a laboratory of the University of Verona. These participants volunteered to take part in the study as a control group. The inclusion criteria for this group included being between 45 and 75 years of age, to match the age range of the BCS group. Additionally, participants were required to be free from any diagnosed cardiovascular or musculoskeletal disorders and to have no self-reported awareness of any condition that could contraindicate physical activity. Exclusion criteria included prior participation in Nordic Walking (NW) courses. Participants were included after passing the Physical Activity Readiness Questionnaire (PAR-Q) (Shephard, 1988; Thomas et al., 1992). The local Ethics Committee approved this study (prot. #39/2023), and all the participants gave their written informed consent.

3.2.2 Study Design

Prior to the training sessions, each participant underwent a private interview to evaluate their prior physical activity background and level of confidence with technology. After recruitment, eight introductory NW sessions were conducted twice a week, with the goal of introducing participants to the correct NW technique. During the last lesson, a 10-minute walking test with electronic poles was performed on a standardized flat surface to assess NW technique (T0).

Next, a further cycle of eight NW sessions was conducted twice per week. During these sessions, the women were randomly divided into two groups. One group used the electronic poles (EP), while the other group used standard NW poles (SP). The participants who used the SP attended the other lessons as usual, receiving feedback directly from the instructor. Participants who used the EP recorded their walking at the beginning and end of each lesson (intra-session measurements) and received feedback during each lesson based on the data recorded with the E-Poles in the previous lesson. Again, during the last lesson, a 10-minute walking test with the electronic poles was performed by everyone on a standardized flat surface (T1). Summarized in (**Fig. 1**).

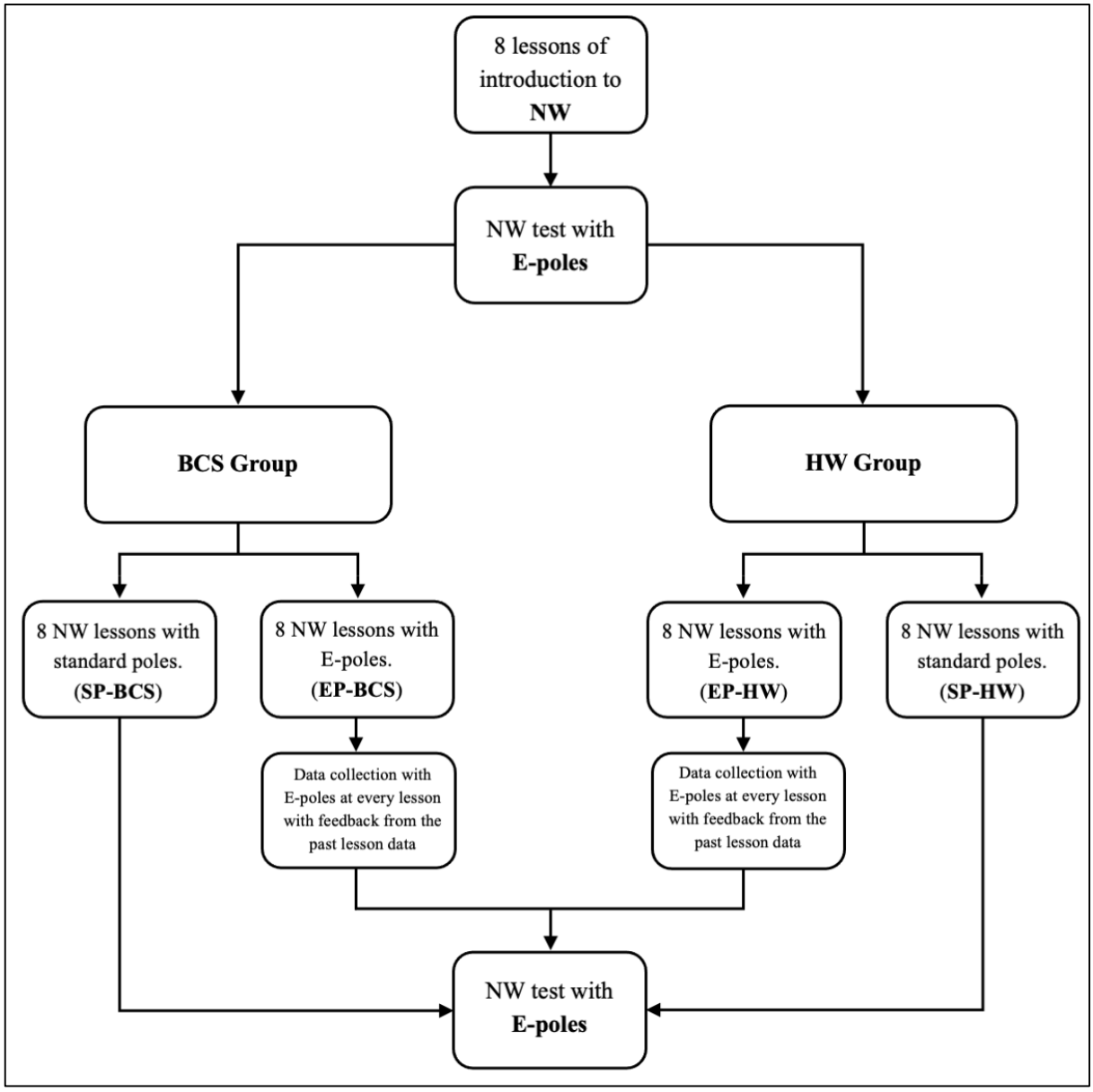

Fig. 1: Study Design

3.2.3 E-Poles and Feedback

The sensorized poles were developed in a commercial system known as E-Poles (Gabel, Rosa [VI], Italy). The measuring unit is an electronic-digital monitoring system integrated inside the handgrip of a length-adjustable carbon-made pole shaft (*E-Poles – Digital poles*, s.d.). The unit embeds a triaxial accelerometer (16-bit resolution, ±8g range, 50 Hz sampling frequency), data storage, and a microcontroller to manage data acquisition and storage, as well as time synchronization of the two poles of the same pair. Data acquisition and processing are handled by a smartphone application (APP Vr: 0.5.17) connected via Bluetooth. After each session, the data are downloaded and sent to the cloud, where they are analyzed using a custom processing library. The results are then visualized through either the smartphone app or a PC application.

The use of a dedicated app returns angular and temporal parameters of NW, along with the distinction between left and right arms, evaluative indices, and geolocation of the training performed. The parameters calculated by the system, as far as temporal parameters are: the cycle time (CT), the pole contact time (PCT), and the duty cycle (DC), which is computed as the ratio between PCT and CT. As far as the pole inclination in the sagittal plane, the average angle (inc_avg[º]) is the average of the angular values assumed during the contact phase of the pole with the ground. The starting angle (inc_on [º]) is the angle at the start of the pole contact phase.

Comparing data from the right and left poles of the previously mentioned parameters enables the assessment of movement symmetry. The indices describing symmetry are: Left/Right Alternation Regularity (l/r_alt [%]) – Measures whether the cycle of one pole starts midway through the cycle of the opposite pole, indicating correct alternation.

Grasp-to-Cycle Regularity (l/r_grasp [%]) – Assesses timing regularity between grasp events and overall cycle phases. Contact Time Symmetry (l/r_Ct [%]) – Quantifies similarity in contact duration between the left and right poles. Angle Symmetry (l/r_inc [%]) – Evaluates the degree of symmetry in average pole angles during each cycle. All the parameters are summarized and explained in **Table. 1**.

During the second phase of the 8 NW lessons, the subjects included in the E-Poles group received feedback from the instructor on the NW techniques, based on the data recorded in the previous NW session.

The feedback provided to participants was based on the data collected during the previous session and was delivered during the central phase of the subsequent lesson. Each participant received personalized feedback, tailored to their individual performance, as reflected in the recorded data. Particular emphasis was placed on key parameters as: 1) L/R contact symmetry, 2) L/R Angle symmetry, 3) L/R pace regularity, 4) Grasp/cycle regularity. Nonetheless, the feedback was not limited only to these variables; all the parameters were also taken into account to provide a more comprehensive overview of each participant's movement patterns.

Tab.1: Description of all parameters derived from the E-Poles.

Parameters	Description	Unit
Cycle time	Time of the whole cycle: flight time + ground time	(s)
Pole contact Time	Time spent by the pole in contact with the ground	(s)
Duty cycle	Pole contact time/cycle time	(% cycle)
NW time	Time of Nordic Walking activity	(min)
N. cycles	Number of cycles recognized as Nordic Walking activity	
N. grasps	Number of openings/closings of the hand on the grip	
Cycles per min	Cycle frequency	(cycles/min)
Average angle	Average angle of the pole during ground contact for the entire Nordic Walking Activity	(°)
Placement angle	Angle of the pole at the beginning of the ground contact	(°)
Uplift angle	Angle of the pole at the end of the ground contact	(°)
Angular range	Difference between the Placement angle and the Uplift angle	(°)
L/R pace regularity	Checks if the activity is executed with a correct time alternation of the left and right cycle (the right cycle starts in the middle of the left cycle and vice versa)	(%)
Grasp/cycle regularity	Checks if the activity is correctly executed: opening/closing the hand around the grip at every cycle	(%)
L/R contact symmetry	Checks the symmetry between left and right ground contact time	(%)
L/R Angle symmetry	Checks the symmetry between left and right contact angles	(%)

3.2.4 Training Characteristics

The same kinesiologist and NW instructor, certified by the ANWI (Association Nordic Walking Italy) and trained in the INWA method (Maas et al., 2023), who was also specialized in physical exercise for BCS, conducted and supervised all sessions for both the BCS and HW groups. In addition, at each location, there was at least one additional NW instructor. For the BCS group, this additional instructor was also specialized in working with BCS. Both the BCS and the HW groups followed the same training program. The first round of eight lessons focused on learning the NW technique, with sessions held twice a week.

Each lesson followed the same structure: a 15-minute warm-up, 45 minutes for the central phase, and a 10-minute cool-down. The warm-up began with exercises targeting the ankle, knee, hip, and shoulder joints. In some cases, poles were also used to intensify the exercises. The central phase of the first eight lessons included exercises for learning the Nordic Walking technique, following the INWA model. The instructors provided all participants with personal advice and strategies to put into practice, aiming to improve their technique.

In the second round of eight sessions, the main focus was on walking while using the correct and complete NW technique, along with some exercises to refine it and specifically train certain elements, such as the ample flexion-extension of the shoulder. The training frequency remained twice per week, but the group was divided into two subgroups: one used SP, while the other used the EP. Both groups have followed the same training structure as in the previous phase: 15-minute warm-up, 45 minutes for the central phase, and a 10-minute cool-down. But the EP groups also completed two recordings with the E-Poles, in each session, one after the warm-up and one before the cool-down, of approximately five to seven minutes while performing NW in a standardized path.

During the central phase of the second round of the eight NW lessons, both the SP group and the EP group were trained at varying intensities and were asked to focus their attention on the accuracy and fluidity of the complete INWA Nordic Walking technique. The difference between the two groups was the method used to provide technical feedback, as early explained in the 'Study Design' section of this chapter. To be more specific, no target intensity was prescribed or systematically monitored in either phase. Sessions during the first block primarily focused on learning and refining the NW technique with shorter walking bouts, suggesting that the actual training intensity was unlikely to exceed a light-to-moderate level. During the second block, although correct technique was consistently prioritized over pace or distance, the progressive increase in walking distances suggests a shift toward a moderate intensity level. Nevertheless, training load was not standardized and may have varied across sessions and participants, although groups were formed to include participants with as similar a level as possible.

3.2.5 Statistical Analysis

In this pilot study, the statistical analyses were restricted to the four E-Poles–derived variables that were directly used to generate automated feedback during the Nordic Walking lessons: 1) L/R contact symmetry, 2) L/R Angle symmetry, 3) L/R pace regularity, 4) Grasp/cycle regularity. All analyses were performed in R (R Foundation for Statistical Computing) using lme4**,** glmmTMB**,** mgcv**,** ARTool**,** DHARMa, and performance. Because each participant contributed repeated observations across baseline and post-intervention tests (T0, T1) and up to eight supervised lessons, we first fitted intercept-only linear mixed-effects models to estimate the intraclass correlation coefficient. When the between-subject variance was non-negligible, outcomes were analyzed using mixed-effects models that included a random intercept for participant (id). For one regularity index with a very low intraclass correlation, marginal (non-mixed) models were preferred. Given the bounded and/or positively skewed nature of the E-Poles indices, we used generalized linear (mixed) models with appropriate distributions and link functions.

Variables expressed as percentages on a 0–100% scale were rescaled to the (0,1) interval and modeled with Beta regression (beta_family with logit or related links), whereas strictly positive, right-skewed variables were modeled with Gamma distributions and log links. For several outcomes, mean–dispersion parameterizations were adopted in glmmTMB, specifying separate formulas for the conditional mean and the dispersion to allow the precision of the distribution to vary across cancer status (breast cancer survivors vs. women without a history of breast cancer), intervention group (E-Poles vs. conventional poles), time, and lesson number. The fixed-effects structure typically included cancer status, intervention group, time (T0 vs. T1, coded as a factor or numeric variable), and lesson number (1–8). When the evolution across lessons was expected to be non-linear, lesson number was modeled using regression splines (natural cubic splines in glmmTMB or smooth terms in generalized additive (mixed) models fitted with mgcv), while retaining a random intercept for participant where appropriate. When necessary, additional covariates were considered, including age (centered and standardized), prior motor experience, self-reported confidence in technology, adherence to supervised lessons (first vs. second half of the program), and baseline values of the outcome (using an ANCOVA-type specification). Covariates were retained only when they improved model fit according to Akaike's Information Criterion and likelihood-ratio tests. Model assumptions and fit were evaluated using graphical and simulation-based diagnostics (DHARMa and performance), with an inspection of residual distributions, dispersion, heteroscedasticity, multicollinearity, and influential observations. In a few cases, highly influential observations identified via Cook's distance were excluded, and the models were re-estimated. For one outcome in which an acceptable residual behavior could not be obtained despite transformation and generalized modeling, a non-parametric aligned rank transform (ART) factorial ANOVA was applied to the cancer × E-Poles design, and, when needed, simple effects and pairwise contrasts were derived from the corresponding ART models using estimated marginal means.

Adherence to the second block of sessions (lessons 9–16, expressed as the percentage of attended sessions) was analyzed using a two-way ANOVA with cancer status (BCS vs. HW) and pole type (E-Poles vs. conventional poles) entered as fixed factors.

3.3 Results

Table 1 reports the mean values ± SD of the four variables, which are the four E–poles–derived variables directly used to generate automated feedback during the NW lessons. **Figure 1** shows the Lesson-by-lesson trend of the L/R pace regularity from lesson 1 to lesson 8, of the second round of eight sessions.

L/R contact symmetry (l/r_Ct) was analyzed using linear mixed-effects models and beta mixed models with a random intercept for participant. In all models, there were no significant main effects of cancer status or pole type (EP vs SP), and no significant cancer status × pole-type interaction (all $p > .05$). Extending the models with age, prior motor experience, confidence with technology, and adherence did not materially change the results or improve model fit.

L/R angle symmetry (l/r_inc) indices were analyzed with linear mixed-effects models and beta mixed models on rescaled proportions. No significant main effects of cancer status or pole type and no significant cancer status × pole-type interaction were detected (all $p > .05$). Additional models including age, prior motor experience, confidence with technology, adherence, or baseline-like covariates did not yield any fixed effects reaching the conventional significance threshold and did not improve Akaike's information criterion. Generalized additive beta models with lesson number treated as a smooth term confirmed the absence of significant fixed effects.

For L/R pace regularity (l/r_alt), violations of distributional assumptions in generalized linear mixed models led to the use of an aligned rank transform (ART) factorial ANOVA for the cancer status × pole-type design. The ART ANOVA showed no significant interaction between cancer status and pole type ($p = 0.679$). The main effect of pole type was significant ($p = 0.013$), with higher l/r_alt values in the EP condition than in the SP condition. Simple-effects analyses indicated that

the contrast between EP and SP was significant in women without a history of breast cancer (higher l/r_alt with EP; $p = 0.029$) and non-significant, but in the same direction, in breast cancer survivors ($p = 0.193$).

For comparisons by cancer status within pole type, a significant difference was observed only in the EP condition ($p = 0.001$), with lower values in BCS than in HW. In a longitudinal beta model with a mean–dispersion specification that included time and lesson number, no significant interaction between cancer status and pole type was detected.

Grasp/cycle regularity (l/r_grasp) was analyzed using beta mixed models with a random intercept for participant. In the basic model including cancer status, pole type (EP vs SP), and their interaction, none of the fixed effects reached statistical significance (all $p > .05$). When baseline values and covariates (age, prior motor experience, confidence with technology, and adherence) were added in an ANCOVA-type specification, model fit did not improve and the effects of pole type and the cancer status × pole-type interaction remained non-significant. A longitudinal beta model with separate mean and dispersion components, including time and lesson number, confirmed the absence of a significant interaction between cancer status and pole type.

Adherence to the second block of sessions differed significantly by pole type, with higher adherence in the EP groups than in the SP groups ($F(1,55) = 13.70$, $p < .001$), whereas neither the main effect of cancer status nor the cancer status × pole-type interaction reached significance (both $p > .20$).

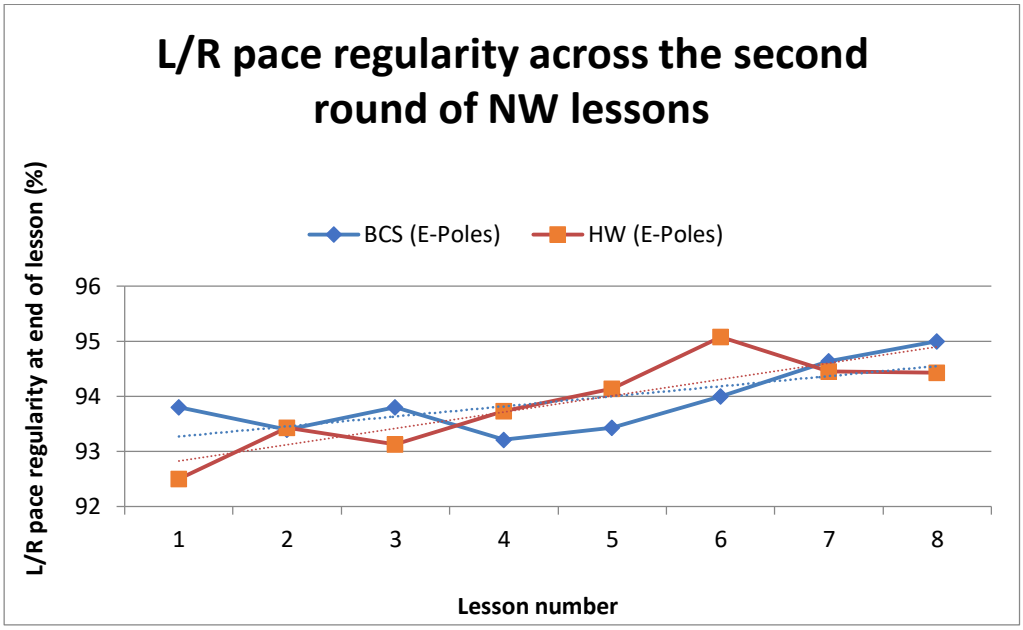

Fig.1. Lesson-by-lesson trend of L/R pace regularity. Dots represent mean values measured at the end of each lesson.

	BCS (n=30)				HW (n=29)			
	EP		SP		EP		ST	
	T0	T1	T0	T1	T0	T1	T0	T1
L/R contact symmetry (%)	85.6 ± 7.5	86.1 ± 7.0	84.3 ± 7.9	84.3 ± 8.3	84.1 ± 13.4	83.3 ± 10.5	78.9 ± 23.9	86.4 ± 6.3
L/R angle symmetry (%)	89.4 ± 5.1	90.1 ± 4.6	88.5 ± 7.8	86.6 ± 7.8	85.6 ± 7.7	89.1 ± 5.9	91.2 ± 4.0	91.0 ± 4.9
L/R pace regularity (%)	93.5 ± 2.4	94.3 ± 1.4	92.1 ± 3.9	92.4 ± 4.0	93.3 ± 3.4	94.4 ± 3.4	85.4 ± 24.8	93.9 ± 1.6
Grasp/cycle regularity (%)	68.3 ± 21.1	80.3 ± 16.7	63.9 ± 25.2	72.9 ± 24.9	78.1 ± 16.8	75.9 ± 21.5	64.7 ± 27.4	57.1 ± 28.1

Table 1. Mean ± SD values of the E-Poles indices used to provide feedback.

3.4 Discussion

The primary objective of this pilot study was to assess the real-world applicability of a novel sensorized pole system designed to support the learning and practice of the NW technique within structured exercise programs. More specifically, we aimed to determine whether delivering a training program based primarily on feedback derived from data collected by the technology embedded in the poles can be an effective approach for improving technique and assisting professionals in their instructional work. Lastly, we explored the potential differential impact of this approach between breast cancer survivors (BCS) and healthy women (HW). The overall findings suggest that the E-Poles system is feasible for implementation in a real-world context and can help refine specific aspects of the NW technique without compromising the global movement pattern established through standard instruction. This can already be regarded as a primary result, as highlighted in the literature (Homma et al., 2016; Pellegrini et al., 2018), where having a correct NW technique is considered relevant for fully achieving the benefits associated with this form of exercise.

This framework is broadly consistent with the behavior of the L/R pace regularity index, one of the metrics used to drive the automated feedback provided by the E-Poles. Within the E-Poles groups, this index showed a small tendency to increase over the course of the program, suggesting that automated feedback may have contributed to a slightly more consistent and rhythmic alternation pattern. More generally, the progressive increase in alternation symmetry can be considered an indication of improved coordination and overall movement quality during NW. BCS and HW generally changed in the same direction, with BCS retaining a somewhat less regular alternation pattern overall, which is plausible given their clinical status.

By contrast, the other technique-related variables, such as pole ground contact duration, contact-time symmetry, angular symmetry, and grip-related measures, showed no clear differences between groups or conditions and, importantly, no systematic worsening in participants using E-Poles.

However, the regularity of grasp/cycle deserves a brief mention: although descriptive values suggested an increase in the E-Poles groups, this apparent improvement was not sufficiently consistent across participants to be regarded as a clear, robust technical advantage. Meanwhile, the symmetry indices remained essentially stable over the intervention, and grip regulation did not display maladaptive patterns. Thus, in both BCS and HW, the use of automated pole-based technical evaluation was not associated with any loss of technical quality. Taken together, these findings suggest that a teaching approach in which automated pole-based feedback plays a central role may be a viable strategy for maintaining the level of technique already achieved, while also suggesting a modest tendency toward more regular alternation without compromising the core features of the NW pattern.

However, some limitations of this approach should be acknowledged. Although the feedback was driven by data collected from the sensorized poles, the sessions were not truly unsupervised, as all participants were trained in the presence of instructors within a structured group setting. A logical next step will be to test the system in genuinely remote or distance-based lessons, where participants rely primarily on feedback derived from E-Poles data.

Going beyond biomechanical considerations, it is also worth noting that participants in the E-Poles groups maintained higher adherence to the program, which may represent an important result from a public health perspective, given the crucial role of sustained participation in maximizing the long-term benefits of exercise interventions.

3.5 Conclusion

Our results should still be regarded as highly preliminary, as the E-Poles system represents an entirely novel tool in the context of NW. Nevertheless, this pilot study indicates that a sensorized pole system providing automated feedback can be successfully integrated into structured NW programs and used to monitor and guide technique in both BCS and HW. Future studies using larger samples and more diverse, heterogeneous training protocols will be essential to confirm and extend the present findings.

4 STUDY 3 – LEARNING NORDIC WALKING TECHNIQUE WITH SENSORIZED POLES AND AUTOMATED FEEDBACK IN BREAST CANCER SURVIVORS AND HEALTHY WOMEN: A PILOT COMPARATIVE STUDY

Abstract

Purpose: This controlled longitudinal study investigated the effects of an 8-week Nordic Walking (NW) program on functional capacity, flexibility, shoulder range of motion (ROM), and static balance in breast cancer survivors (BCS), and compared these adaptations with those observed in healthy women (HW) exposed to the same intervention.

Methods: 59 (30 BCS, 56.6 ± 7.9 years; 29 HW, 60.0 ± 9.1 years) completed a 16-session NW program (two 8-lesson blocks, twice weekly) delivered according to the INWA method and primarily oriented toward technique learning. Assessments were performed at baseline (T0), after the first 8 sessions (T1), and after 16 sessions (T2). Kinesiological outcomes included handgrip strength, 30-s sit-to-stand, single-leg back bridge endurance, back scratch, and sit-and-reach tests. Shoulder ROM (flexion, abduction, adduction, extension on both sides) was measured with an inertial sensor, and static balance (sway area and path length, eyes open) was assessed using an OptoJump–Gyko system. Linear mixed-effects models with time (T0, T1, T2) and group (BCS, HW) as fixed factors were applied; additional models in BCS only tested the effect of cancer localization side. Exploratory median-split analyses were conducted to investigate whether baseline sway area influenced balance responses.

Results: Both groups demonstrated clear improvements in lower-limb and trunk performance, with sit-to-stand repetitions and single-leg back bridge endurance increasing over time (all $p < 0.001$). The BCS generally exhibited lower bridge times than the HW (right side, $p = 0.008$; left side, $p = 0.094$), but showed similar relative gains (time × group, $p \geq 0.795$). In contrast, maximal handgrip strength did not display robust training-related improvements (time effects, $p \geq 0.291$). BCS were slightly stronger than HW throughout (group effects, $p \leq 0.027$), and cancer side was not associated with handgrip outcomes (all $p > 0.10$). BCS consistently showed greater hamstring and lower-back flexibility than HW in the sit-and-reach test (group $p = 0.007$), but without a meaningful pre–post change (time $p = 0.187$; time × group $p = 0.245$). In contrast, back scratch improved over time on both sides

in both groups (right side time $p = 0.015$; left side time $p = 0.027$; all other $p \geq 0.107$). Shoulder ROM increased across all movements (time $p \leq 0.002$), with HW presenting slightly higher flexion and abduction than BCS (group $p < 0.001$ for flexion; $p = 0.008$ for abduction) and a more progressive extension gain (extension time × group $p = 0.002$); however, both groups reached comparable values by T2. Static balance analyses revealed overall reductions in sway area and path length (time, $p = 0.006$ and $p < 0.001$, respectively), with HW tending to exhibit larger decreases in sway path (time × group, $p < 0.001$). Exploratory stratification suggested that women with poorer baseline balance (higher sway area) showed the most improvement (high-sway subgroup, time $p < 0.001$), whereas those with better baseline balance largely maintained their initially favorable stabilometric profile (low-sway subgroup, time $p = 0.198$; time × group $p = 0.012$).

Discussion: An 8-week, technique-focused NW program elicited meaningful gains in functional lower-limb and trunk performance, shoulder flexibility, ROM, and static balance in both BCS and HW, while leaving hamstring–lumbar flexibility and maximal handgrip strength largely unchanged. These findings support NW as a feasible, multicomponent exercise modality capable of addressing several clinically relevant domains in BCS without compromising balance, and highlight the need for future trials manipulating NW training dose and content to clarify dose–response relationships and optimize protocols for both clinical and non-clinical populations.

4.1 Introduction

Breast cancer is one of the most frequently diagnosed neoplasms in women worldwide (Sung et al., 2021; WHO, 2025a). However, despite this high incidence, the survival rate has increased substantially over the last few decades, thanks to screening strategies and continuous therapeutic progress (Amato et al., 2023). As a consequence, the number of women living after a breast cancer diagnosis is steadily growing, and in high-income countries, 5-year survival rates now exceed 90% (Soldato et al., 2023; WHO, 2025b).

With rising survival rates, clinical and scientific attention has progressively moved beyond acute care to address the long-term outcomes of traditional breast cancer management, many of which may remain evident even years after treatment completion (Agrawal, 2014), and are accompanied by a range of long-term kinesiological sequelae. These long-term physical sequelae are often interrelated and may present as reduced functional capacity and limitations in daily activities, chronic pain, and postural and balance impairment (Joly et al., 2019; Lovelace et al., 2019; Winters-Stone et al., 2019; Mehra et al., 2024). Among these, upper-limb morbidity is particularly frequent and is often accompanied by lymphedema, shoulder stiffness, or limited range of motion (ROM), and axillary web syndrome (Rietman et al., 2006; Hauerslev et al., 2020; Koehler et al., 2022). All together, these impairments coexist within the same clinical picture, contributing to reduced strength, aerobic capacity, shoulder mobility, and overall movement efficiency, and ultimately restricting personal autonomy and participation in social or occupational roles (Winters-Stone et al., 2019; Jørgensen et al., 2021; Lippi et al., 2022; Macdonald et al., 2024).

Physical exercise is increasingly acknowledged as a central strategy for preventing or attenuating the kinesiological long-term side effects of breast cancer treatments (Hayes et al., 2019).

However, to effectively address this wide range of problems, current evidence and clinical recommendations emphasize the need for multimodal exercise prescriptions for breast cancer survivors (BCS), which combine aerobic and resistance training with flexibility, proprioception, and balance components, and tailor these elements to patients' symptoms and treatment phase (Campbell et al., 2019; Hayes et al., 2019; Schmitz et al., 2019). Among the various multi-component exercise approaches proposed for BCS, Nordic Walking (NW) has attracted increasing interest. NW combines an aerobic component with active upper-limb engagement and coordinative demands, while remaining simple to deliver and easily transferable to real-world, community-based settings. Despite the protocols described in the literature are often heterogeneous in terms of training duration, intensity, supervision, and selected outcomes, the available evidence, summarized in recent reviews, indicates that NW is feasible and safe in oncology and that, in breast cancer survivors, it may support improvements across several relevant domains like physical fitness and muscle strength, self-reported physical activity, and breast-cancer–related symptom burden (including lymphedema and perceived disability) (Sánchez-Lastra et al., 2019; Casanovas-Álvarez et al., 2025). Despite this growing interest and the expanding number of publications on NW in BCS, its effects still need to be clarified more systematically. Most studies focus exclusively on clinical cohorts, with limited direct comparison to healthy women exposed to the same training stimulus (Sánchez-Lastra et al., 2019; (Casanovas-Álvarez et al., 2025; Sturgeon et al., 2023).

Therefore, the primary objective of this controlled longitudinal study is to assess the impact of an 8-week NW program on functional capacity, balance, and flexibility in BCS, comparing these changes with those observed in a group of healthy women (HW) undergoing the same intervention. We hypothesized that the NW program would lead to improvements in functional capacity, flexibility, and balance in both groups, and result in a whole-body form of exercise with at least comparable or possibly larger gains in BCS.

4.2 Materials And Methods

4.2.1 Subjects

This study enrolled 59 women divided into two groups. The first group included 30 BCS (mean age ± standard deviation: 56.6 ± 7.9 years). These participants were recruited from the Integrative Medicine Outpatient Clinic of ASL 02 Lanciano-Vasto-Chieti at the "G. Bernabeo" Hospital in Ortona and from the Department of Medicine and Aging Sciences at the University "G. D'Annunzio" of Chieti-Pescara. Inclusion criteria to participate in the intervention were medical eligibility to NW, a minimum of 6 months after breast cancer surgery. Exclusion criteria included current chemotherapy, current radiotherapy, and active diseases that could limit participation in NW, as well as prior participation in NW courses. The term "current" refers to the date of the baseline evaluation of each participant. Data were collected from January 2024 to May 2024. The local Ethics Committee approved this study (protocol #312/2015), and all participants provided written informed consent. The second group of 29 HW (mean age ± standard deviation: 60 ± 9.13 years) was recruited at the CeRiSM – Research Center for Sport, Mountain and Health in Rovereto, a research center of the University of Verona. These participants volunteered to take part in the study as a control group. The inclusion criteria for this group included being between 45 and 75 years of age, to match the age range of the intervention group. Additionally, participants were required to be free from any diagnosed cardiovascular or musculoskeletal disorders and to have no self-reported awareness of any condition that could contraindicate physical activity. Exclusion criteria included prior participation in Nordic Walking (NW) courses. Participants were included after passing the Physical Activity Readiness Questionnaire (PAR-Q) (Shephard, 1988; Thomas et al., 1992). The local Ethics Committee approved this study (protocol #39/2023), and all participants provided written informed consent.

4.2.2 Study Design

Both groups followed the same study design (**Fig. 1**). At baseline (T0), participants underwent a series of tests to assess static balance (Body Sway), muscular strength, flexibility, and shoulder joint range of motion (ROM).

Subsequently, eight introductory NW sessions were conducted twice a week, with the goal of introducing the participants to the correct NW technique. At the end of this period, all tests were repeated (T1).

Next, a further cycle of eight NW lessons was conducted twice per week. Finally, the participants underwent the physical, balance, and ROM tests again (T2).

4.2.3 Kinesiological Evaluations

Handgrip strength.

The handgrip test (Roberts et al., 2011a; Cantarero-Villanueva et al., 2012) measures the maximum isometric strength of the hand and forearm muscles. The measurements of this parameter have been included as a simple marker of global muscle strength and functional reserve, since lower grip strength is associated with higher mortality risk and greater odds of disability and loss of independence in older adults (Rantanen, 1999; López-Bueno et al., 2022; Andersen et al., 2024). It was performed by using an electronic hand dynamometer (EH101, Camry Electronic Zhongshan, Guangdong, China) for the BCS groups, and a hydraulic hand dynamometer (SH5001, Saehan, MVS In Motion, Tisselt, Belgium) for the HW groups. Each participant stood with their arm extended, the wrist in a neutral position. The test was executed three times with the dominant hand and three times with the non-dominant hand. The best-recorded value for each side was considered for the data analysis.

Sit to Stand test:

Sit-to-Stand performance was included as a pragmatic indicator of lower-limb functional strength and power, closely related to mobility limitations and the ability to perform everyday transfers such as rising from a chair (Alcazar et al., 2018). To

begin, the test needs a chair with a straight back and no armrests, blocked against a wall. The person sits in the center of the chair, with their arms crossed, their palms on their shoulders.

The feet must stay flat on the floor, and the back must be straight. From a seated position, the person stands up to a fully upright position and then returns to a seated position. This is repeated for 30 seconds. The total number of times the person reaches a fully upright position within 30 seconds is counted. The final score of the test is represented by the number of times the participant successfully reaches the upright position during the 30 seconds.

Single-leg back bridge test:

The single-leg back bridge test was included to assess hip and trunk extensor endurance, providing insight into posterior-chain function that supports gait, posture, and stable performance of daily activities (Butowicz et al., 2016). The test was performed with the participant lying supine with knees in flexion and feet flat on the ground. The participant performed a double-leg hip bridge, reaching a posterior 90-degree angle of the knee joint. Once a neutral spine and pelvis position were achieved, the participant was asked to extend one knee (randomly determined) so that the leg was straight and her thighs were parallel to each other. The participant was asked to hold this position as long as possible. The test was terminated when the participant was no longer able to maintain the position or when the subject reached the 3-minute time limit. One attempt was carried out for each side.

Back scratch test:

The back scratch test was included as a measure of shoulder flexibility and upper-limb function, which are often affected in breast cancer survivors and are important for everyday tasks (Rikli & Jones, 1999; Macdonald et al., 2024). Participants began the test in a standing position, placing one arm/hand on their lower back and moving it up the spine toward their head. The opposite arm/ hand was placed behind their neck, moving it down the spine, aiming to put the long finger of each hand as near each other as possible or to overlap the other hand as much as possible. The procedure was repeated, reversing the order of the arm/hand. The gap between the

fingertips of the long fingers of both hands was measured to the nearest half cm using a centimeter rod. Positive numbers were used if the fingers overlapped, and negative numbers if the fingers did not meet. The task was tested three times for each limb. The best measure for each limb was considered.

Sit and reach test:

The sit-and-reach test was included as an index of hamstring and lower-back flexibility, a domain commonly assessed in functional fitness batteries and relevant for bending, lifting, and other daily movements (Wells & Dillon, 1952; Mayorga-Vega et al., 2014). A standardized box was placed on a wall, and the participants sat on the floor with their knees and upper body straight and their heels against the box without shoes. The participants extended their arms as far as possible along the measuring tape at the top of the box, with one hand on top of the other, sliding along the box with their back and legs straight. The measured value was recorded with precision to the nearest mm. Three attempts were made, and the best result was considered.

4.2.4 Shoulder ROM Evaluations

Shoulder mobility was measured using a wireless inertial sensor (Gyko, Microgate Italia, Bolzano, Italy) sampling at 1000 Hz. The Gyko was attached to the participant's wrist and secured with the manufacturer's Velcro strap. The assessment included four active shoulder movements: flexion, abduction, adduction, and extension. Flexion and abduction were performed in an upright standing position with heels and shoulders against the wall, in order to maintain a neutral trunk posture as much as possible. Medial shoulder adduction was performed starting from the arm alongside the trunk, moving the arm in a medial direction in the frontal plane. Shoulder extension was performed while standing, facing the wall, with the toes touching the wall and the gaze directed towards it, as the arm was moved backward in the sagittal plane.

For each movement, participants first performed a short familiarization trial and then three recorded trials at a self-selected speed and range of motion, with the instruction not to exceed their shoulder pain limit. Data were processed using the proprietary GykoRePower software (Microgate Italia, Bolzano, Italy) to obtain, for each movement, the shoulder range of motion (degrees - °). The best value across the three recorded trials was used.

4.2.5 Static Balance Assessment

Static balance was assessed in the standing position using the "Body Sway" protocol of the OptoJump Next system in combination with an inertial sensor (OptoJump Next and Gyko, Microgate Italia, Bolzano, Italy). The Gyko was placed on the upper trunk using the manufacturer's harness, and both sensor placement and standing position were standardized and replicated for all participants. During the test, participants stood with their feet approximately shoulder-width apart, their arms relaxed alongside their bodies, and their eyes open, gazing at a fixed point on the wall in front of them. One 30-second trial was performed in this standardized stance, during which participants were instructed to stand as still as possible. The software automatically computed stabilometric parameters; for the present analysis, only sway area (mm^2; 95% confidence ellipse of the sway trajectory) and sway path length (mm; total length of the sway trajectory) were retained as outcome variables

4.2.6 Training Characteristics

The same kinesiologist and NW instructor, certified by the ANWI (Association Nordic Walking Italy) and trained in the INWA method, who was also specialized in physical exercise for BCS, conducted and supervised all sessions for both the BCS and HW groups. In addition, at each location, there was at least one additional NW instructor. For the BCS group, the additional instructor was also specialized in working with BCS.

Both the BCS and the HW groups followed the same training program (**Fig. 1**). The first round of eight lessons focused on learning the NW technique, with sessions held twice a week.

Each lesson followed the same structure: a 15-minute warm-up, 45 minutes for the central phase, and a 10-minute cool-down. The warm-up began with on-the-spot joint mobility exercises targeting the ankle, knee, hip, and shoulder joints with circling movements. In some cases, poles were also used to intensify the exercises. The central phase of the first eight lessons was focused especially on exercises for learning the NW technique, following the INWA didactic program (Maas et al., 2023). The instructors provided all participants with personal advice and strategies to put into practice, with the goal of improving the technique.

In the second round of eight sessions, the main focus was on walking while using the correct and complete NW technique, along with some exercises to refine it. The frequency remained twice per week. Both groups have followed the same training structure as in the previous phase: 15-minute warm-up, 45 minutes for the central phase, and a 10-minute cool-down.

During the central phase of the second round of the eight NW lessons, groups were trained at varying intensities and were asked to focus their attention on the accuracy and fluidity of the complete INWA NW technique.

To be more specific, no target intensity was prescribed or systematically monitored in either phase. Sessions during the first block primarily focused on learning and refining the NW technique with shorter walking bouts, suggesting that the actual training intensity was unlikely to exceed a light-to-moderate level. During the second block, although correct technique was consistently prioritized over pace or distance, the progressive increase in walking distances suggests a shift toward a moderate intensity level. Nevertheless, training load was not standardized and may have varied across sessions and participants, although groups were formed to include participants with as similar a level as possible.

4.2.7 Statistical analysis

Descriptive statistics are presented as mean ± standard deviation (SD). Kinesiological parameters and shoulder ROM outcomes were analyzed using linear mixed-effects models. For each dependent variable, time (three levels: T0, T1, T2) was entered as a within-subjects fixed factor, and group (BCS vs. HW) was entered as a between-subjects fixed factor, with a random intercept for each participant to account for repeated measures. For the shoulder ROM and handgrip strength outcomes, the same model structure was fitted within the BCS group only.

In this additional analysis, cancer localization side was included as an extra between-subject factor.

Body sway parameters (area and path length) were analyzed using the same linear mixed-effects modeling framework. However, for these variables, time was divided into two levels (T0 and T2), as T1 measurements were excluded from the analysis. In addition, four participants were excluded from the balance analyses due to invalid data, resulting in a final sample of 28 BCS and 28 HW. Main effects and time × group interactions were tested using Type III F-tests, and post-hoc pairwise comparisons for significant terms were adjusted for multiple testing using the Holm method. Model assumptions were checked by visual inspection of residual plots. The level of statistical significance was set at $p < 0.05$. All analyses were performed using JASP (version 0.18; JASP Team, Amsterdam, The Netherlands). Additionally, an exploratory analysis was conducted on the area of body sway by dividing participants into two subgroups based on their median baseline value (T0): below and above the median. This split was conducted to test the hypothesis that participants with markedly different baseline balance levels would exhibit a differentiated evolution over time. Since the subgroups were defined based on the same outcome variable, these analyses were considered descriptive and should be interpreted with caution.

4.3 Results

4.3.1 Kinesiological Evaluations

All the kinesiological mean values, SD, and statistical results are reported in **Table 1**. The right handgrip test showed a main effect of group, $F(1, 56.30) = 5.171$, $p = 0.027$, with lower values for the HW group. No significant effect of time or a group × time interaction**.** Left handgrip test showed a main effect of group, $F(1, 57.18) = 5.833$, $p = 0.019$, BCS showed higher values than HW, but with group × time interaction, $F(2, 99.83) = 4.504$, $p = 0.013$, BCS remained relatively stable; HW had a gradual increase. The main effect of time was not significant. However, post hoc tests (**Table 2**) did not reveal significant within-group changes between consecutive time points. In BCS, handgrip strength slightly increased from T0 to T1 and then tended to decrease from T1 to T2 ($p = 0.075$), while in HW, only small, non-significant increases were observed over time (all $p > 0.075$).

Models that included only breast cancer survivors and added cancer localization as a factor did not show significant main or interaction effects for either right or left handgrip and did not alter the overall pattern of results (all $p > 0.10$).

Table 3 summarizes all post hoc pairwise comparisons that are reported in the section below. In the single-leg back bridge on the right side, there were significant improvements in performance over time, $F(2, 111.00) = 13.185$, $p < 0.001$, and group interaction, $F(1, 56.54) = 7.572$, $p = 0.008$, with lower results for the BCS group, while the group × time interaction was not significant. Post hoc tests indicated significant improvements from T0 to T1 ($p = 0.010$) and from T1 to T2 ($p = 0.017$).

In the single-leg back bridge on the left side, a significant improvement in performance over time was found, $F(2, 111.60) = 12.080$, $p < 0.001$; no significant effects of group or group × time interaction were detected. Post hoc tests indicated significant improvements from T0 to T1 and from T1 to T2 (both $p = 0.023$).

The sit-and-reach performance showed a significant main effect of group, $F(1, 56.12) = 7.990$, $p = 0.007$, with lower flexibility for the HW group. There was no significant main effect of time or a time × group interaction.

Sit-to-stand performance showed a significant increase in reps over time, F(2,

112.52) = 15.935, $p < 0.001$, while the main effect of group and the time × group interaction were not significant. Post hoc tests indicated a significant improvement of reps between T0 and T1 ($p < .001$), whereas the additional change between T1 and T2 did not reach statistical significance ($p = .081$).

The back scratch tests show the same improvements in performance on both sides. The right side showed a main effect of time, $F(2, 112.59) = 4.351$, $p = 0.015$, with no significant effects of group or group × time interaction. However, even if mean values tend to show better performance, post hoc tests did not show significant changes between T0 and T1 or between T1 and T2 (both $p > 0.16$). But post hoc comparison between T0 and T2 confirms the significant improvements ($p = 0.010$). On the left side, back scratch also showed a main effect of time, $F(2, 113.19) = 3.718$, $p = 0.027$; again, no significant effects of group or group × time interaction were observed. The same result observed on the right side was also found on this side, with the post hoc test, showing no significant changes between T0 and T1 or between T1 and T2 (all $p > 0.10$) but a significant improvement between T0 and T2 ($p = 0.025$).

	BCS (n=30)			HW (n=29)			Time (F), p	Group (F), p	Interaction (F), p
	T0	**T1**	**T2**	**T0**	**T1**	***T2***			
Flexibility									
Back scratch – right (cm)	-0.46±6.02	0.62±5.31	1.82±4.96	0.54±5.05	2.35±5.25	3.14±5.46	(4.351), 0.015	(1.726), 0.194	(0.098), 0.907
Back scratch – left (cm)	-5.41±7.41	-2.95±7.05	-4.3±7.38	-5.64±7.77	-3.41±7.36	-0.26±6.06	(3.718), 0.027	(0.812), 0.371	(2.282), 0.107
Sit and reach (cm)	5.43±6.01	5.92±4.94	5.57±8.20	-0.46±9.11	0.50±9.11	3.57±7.52	(1.702), 0.187	(7.990), 0.007	(1.424), 0.245
Strength									
Handgrip – right (kg)	27.2 ± 3.0	29.6 ± 3.1	27.8 ± 4.8	25.9 ± 4.6	25.8 ± 5	26.9 ± 5.2	(0.291), 0.291	(5.171), 0.027	(2.927), 0.058
Handgrip – left (kg)	25.3 ± 4.7	27.4 ± 4.1	25 ± 5.4	22.7 ± 4.4	23 ± 4.8	25 ± 5.2	(0.821), 0.443	(5.833), 0.019	(4.504), 0.013
Single-leg back bridge – right (s)	41.6 ± 24.7	61.1 ± 29.7	73.8 ± 40.4	65.2 ± 37.2	76.9 ± 40.1	91.8 ± 43.7	(13.185), <0.001	(7.572), 0.008	(0.230), 0.795
Single-leg back bridge – left (s)	44.2 ± 28	57.0 ± 37.2	72.1 ± 43.5	50.7± 32.6	69.8 ± 37.1	86.4 ± 45.5	(12.080), <0.001	(2.909), 0.094	(0.177), 0.838
Sit to Stand (reps)	13.5 ± 3.8	15.9 ± 4.3	17.3 ± 4.9	14.5 ± 2.3	17.4 ± 2.8	18.3 ± 4.1	(15.935), <0.001	(3.253), 0.077	(0.089), 0.915

Table 1. Mean values ± SD and statistical results of the kinesiological test.

Group	Contrast	Mean diff (95% CI)	p (Holm)
BCS	T1 – T0	1.696 (−0.654 to 4.046)	0.314
	T2 – T1	−2.572 (−4.715 to −0.429)	0.075
HW	T1 – T0	0.309 (−1.674 to 2.293)	0.760
	T2 – T1	1.835 (−0.149 to 3.818)	0.209

Table 2. Post hoc pairwise comparisons across time for left handgrip strength (time × group interaction). Values are estimated marginal mean differences from the linear mixed-effects model. P-values are Holm-adjusted for multiple comparisons.

Kinesiological Evaluations	Contrast	Mean diff (95% CI)	p (Holm)
Flexibility			
Back scratch – left (cm)	T1 – T0	2.350 (−0.040 to 4.740)	0.107
	T2 – T1	0.870 (−1.480 to 3.220)	0.469
	T2 – T0	3.220 (0.830 to 5.610)	0.025
Back scratch – right (cm)	T1 – T0	1.450 (−0.180 to 3.080)	0.164
	T2 – T1	1.000 (−0.610 to 2.600)	0.223
	T2 – T0	2.440 (0.810 to 4.070)	0.010
Strength			
Single-leg back bridge – left (s)	T1 – T0	16.400 (3.640 to 29.160)	0.023
	T2 – T1	15.750 (3.120 to 28.390)	0.023
Single-leg back bridge – right (s)	T1 – T0	16.303 (4.894 to 27.712)	0.010
	T2 – T1	13.729 (2.439 to 25.019)	0.017
Sit-to-Stand	T1 – T0	2.656 (1.290 to 4.022)	<0.001
	T2 – T1	1.199 (−0.147 to 2.546)	0.081

Table 3. Post hoc pairwise comparisons between time points for kinesiological outcomes. Values are estimated marginal mean differences (95% confidence intervals) derived from linear mixed-effects models with time (T0, T1, T2).
P-values are Holm-adjusted for multiple comparisons. Positive mean differences indicate higher values at the later time point (e.g., T1–T0 > 0 indicates higher scores at T1 than at T0).

4.3.2 Shoulder ROM

Mean values, SD, and statistical results of shoulder ROM are reported in **Table 4**.

Flexion ROM showed main effects of group ($F(1, 51.98) = 12.733$, $p < 0.001$), dominant side ($F(1, 57.10) = 8.503$, $p = 0.005$) and time ($F(2, 49.59) = 22.422$, $p < 0.001$), whereas the group × time interaction was not significant. HW consistently exhibited greater flexion ROM than BCS, with dominant side-shoulder flexion being higher than the non-dominant shoulder flexion, but with flexion ROM increasing from T0 to T2 in both groups. Post-hoc contrasts (**Table 5**) indicated a significant improvement from T0 to T1 ($p < .001$) and a further significant increase from T1 to T2 ($p = .006$).

Abduction ROM also showed main effects of group ($F(1, 56.03) = 6.363$, $p = 0.015$) and time ($F(2, 69.87) = 15.048$, $p < 0.001$), with no significant differences between dominant sides or a group × time interaction. HW consistently exhibited greater abduction ROM than BCS, and that abduction ROM increased from T0 to T2 in both groups, with similar changes in the dominant and non-dominant sides. Post hoc tests (**Table 5**) revealed a significant increase from T0 to T1 ($p = 0.038$) and a further significant improvement from T1 to T2 ($p = 0.032$).

Medial adduction ROM showed a main effect of time, with increased ROM values ($F(2, 56.09) = 8.201$, $p < 0.001$). There were no significant effects of group, dominant side, or their interactions (all $p > 0.15$). Post hoc tests (**Table 5**) indicated a significant increase from T0 to T1 ($p = 0.012$) and a further significant improvement from T1 to T2 ($p = 0.012$).

Extension ROM showed a main effect of time ($F(2, 55.76) = 18.221$, $p < .001$) and a group × time interaction ($F(2, 55.76) = 6.242$, $p = .004$), while the main effects of group and dominance side were not significant. Extension ROM increased in both groups; however, HW displayed a more progressive increase across assessments, whereas BCS remained relatively stable between T0 and T1 and showed a clear improvement only at T2. Indeed, post-hoc contrasts (**Table 5**) showed that in BCS, shoulder extension ROM did not change from T0 to T1 ($p = .668$), but increased significantly from T1 to T2 ($p = .006$).

When the analyses were repeated, including only breast cancer survivors and adding cancer localization side as an additional factor, neither the main effect of localization side nor its interactions with time were significant for any of the four shoulder ROM movements (all $p > 0.10$).

	BCS (n=30)			HW (n=29)			Time (F), p	Group (F), p	Interaction (F), p	Dominant Side (F), p
	T0	**T1**	**T2**	**T0**	**T1**	***T2***				
Shoulder ROM										
Flexion – dominant side (°)	166.5±12	170.3±12.2	176.5±11.2	172.5±10.2	177.5±5.5	179.7±6.8	(22.422), <0.001	(12.733), <0.001	(1.789), 0.178	(8.503), 0.005
Flexion – non-dominant side (°)	163.4±13.4	165.6±12.2	174.1±9.9	167.8±13.5	176.5±5.1	177.5±7.8				
Abduction – dominant side (°)	152±25.7	155.2±25.1	164.1±27.8	162.4±19.1	170.8±12.7	178.6±8.9	(15.048), <0.001	(6.363), 0.015	(2.513), 0.088	(1.044), 0.311
Abduction – non-dominant side (°)	151.2±28.1	154.7±24.8	165.7±22.2	156.3±21.4	169.4±13.5	169.9±20.5				
Adduction – dominant side (°)	103±17.8	105.3±13.8	110.9±15.4	99.5±13.2	107.3±6.8	110.8±13.8	(8.201), <0.001	(0.181), 0.672	(0.219), 0.804	(0.282), 0.597
Adduction – non-dominant side (°)	98±33.7	105±14.4	111.9±14.8	101.5±10.2	107.4±7.3	112±11				
Extension – dominant side (°)	61.8±11.6	61.7±13.4	70.5±15.1	56.6±10.1	63.7±9.3	68±9.1	(18.012), <0.001	(0.153), 0.697	(6.242), 0.004	(0.018), 0.894
Extension – non-dominant side (°)	60.912.9±	59.9±12.5	68.2±11	58.9±9.6	64.6±8	67.7±11.3				

Table 4. Mean values ± *SD and statistical results of the shoulder ROM*.

Shoulder ROM	Contrast	Mean diff (95% CI)	p (Holm)
Flexion	T1 – T0	5.533 (3.275 to 7.792)	<0.001
	T2 – T1	4.504 (1.276 to 7.732)	0.006
Abduction	T1 – T0	7.068 (3.931 to 10.205)	<0.001
	T2 – T1	7.275 (1.547 to 13.003)	0.013
Adduction	T1 – T0	5.957 (1.717 to 10.197)	0.012
	T2 – T1	5.300 (1.157 to 9.444)	0.012

Table 5. Post hoc pairwise comparisons between time points for shoulder ROM outcomes. Values are estimated marginal mean differences (95% confidence intervals) derived from linear mixed-effects models with time (T0, T1, T2. P-values are Holm-adjusted for multiple comparisons. Positive mean differences indicate higher ROM at the later time point (e.g., T1–T0 > 0 indicates higher ROM at T1 than at T0).

Group	Contrast	Mean diff (95% CI)	p (Holm)
BCS	T1 – T0	0.541 (−1.934 to 3.016)	0.668
	T2 – T1	8.099 (2.948 to 13.250)	0.006
HW	T1 – T0	6.678 (4.325 to 9.032)	<0.001
	T2 – T1	3.694 (−1.458 to 8.845)	0.320

Table 6. Post hoc pairwise comparisons across time for shoulder extension ROM (time × group interaction). Values are estimated marginal mean differences (95% confidence intervals) derived from a linear mixed-effects model with time (T0, T1, T2) and group (breast cancer vs. healthy women) as fixed factors and ID as a random intercept. P-values are Holm-adjusted for multiple comparisons. Positive mean differences indicate higher extension ROM at the later time point.

4.3.3 Static Balance

Mean values, SD, and statistical results of the static balance are reported in **Table 7.** For the area of body sway, the model showed a significant reduction in sway area over time, $F(1, 54.0) = 8.316$, $p = 0.006$, while the main effects of group and the time × group interaction were not significant. Meanwhile, for the path length, the model indicated a significant reduction of the length over time, $F(1, 108) = 27.489$, $p < 0.001$, and a significant time × group interaction, $F(1, 108) = 13.185$, $p < 0.001$, with a reduction of values for HW group meanwhile the BCS remained essentially stable but, the main effect of group was not significant.

Post-hoc contrasts (**Table 8**) indicated a reduction in path length from T0 to T2 in HW ($p < .001$), whereas BCS exhibited only a small, non-significant change ($p = 0.254$).

In the exploratory analysis **(Table 9)**, participants were split according to the median sway area at baseline (median: 585.92 mm^2).

A mixed-design repeated-measures ANOVA was conducted on body sway area, with time (T0, T2) as the within-subject factor and group (BCS, HW) as the between-subjects factor. In the subgroup with the low values of the body sway, no main effect of time and no main effect of group were found, but a significant time × group interaction, $F(1, 26) = 7.210$, $p = 0.012$, with an increase in the value in BCS and a small reduction in HW. Post-hoc comparisons indicated that sway area increased significantly from T0 to T2 in BCS ($p = 0.031$), whereas no significant change over time was observed in HW. In contrast, in the subgroup with the high baseline sway area, the same ANOVA showed a significant decrease in values over time, $F(1, 26) = 17.173$, $p < 0.001$, while the main effect of group and the time × group interaction were not significant.

	BCS (n=28)		HW (n=28)		Time (F), p	Group (F), p	Interaction (F), p
	T0	**T2**	**T0**	***T2***			
Body Sway							
Area (mm²)	778.7±783.3	661.5±490.7	838.0±603	443.7±256.4	(8.316), 0.006	(1.407), 0.241	(0.223), 0.638
Length (mm)	486.6±356	462.3±144.7	620.1±120.7	235.6±49.2	(27.489), < 0.001	(2.347), 0.128	(13.185), < 0.001

Table 7. Mean values ± SD and statistical results of the static balance test included in the linear mixed-effects model analyses.

Group	Contrast	Mean diff (95% CI)	p (Holm)
BCS	T2 – T0	−69.858 (−189.984 to 50.268)	0.254
HW	T2 – T0	−384.592 (−504.718 to −264.466)	<0.001

Table 8. Post hoc pairwise comparisons across time for sway path length (time × group interaction, T0 vs. T2). Values are estimated marginal mean differences (95% confidence intervals) derived from a linear mixed-effects model with time (T0, T2) and group (breast cancer vs. healthy women) as fixed factors and subject as a random intercept. P-values are Holm-adjusted for multiple comparisons. Negative mean differences indicate lower sway path length at T2 than at T0.

	BCS (n=28)		HW (n=28)		Time (F), p	Group (F), p	Interaction (F), p
	T0	**T2**	**T0**	***T2***			
Body Sway							
Above median Area (mm²)	2052.8±2171.6	1071.7±991.6	1151.8±632.6	523.1±300.2	(1.743), 0.198	(0.411), 0.527	(7.210), 0.012
Median Value (mm²)			**585.9**				
Below median Area (mm²)	304.3±132.2	544.4±408.5	419.6±111.7	337.8±130.7	(17.173), < 0.001	(3.309), 0,080	(0.823), 0.373

Table 9. Mean values ± SD of the sway area based on the median split groups division. Post-hoc shows sway area increased from T0 to T2 in BCS (p = 0.031); HW: no significant change over time.

4.4 Discussion

As outlined in the introduction, the primary aim of this study was to evaluate the impact of an 8-week Nordic walking program on multiple aspects of functional ability, such as strength, balance, and flexibility BCS and to compare these effects with those observed in a group of healthy women (HW) undergoing the same intervention. In general, our results can reinforce the concept that NW represents an effective multi-component form of exercise, not only for patients recovering from interventions or therapies but also for a healthy population, in line with previous literature. (Grigoletto et al., 2022; Morano et al., 2024). However, a closer inspection of the different outcome domains revealed a particular pattern of adaptation. Specifically, when examining strength-related outcomes on the lower-limb and trunk, such as the sit-to-stand and single-leg back bridge tests, on either the left or right side, both groups demonstrated improvements over time, supporting the notion that NW is not merely an aerobic activity but a form of exercise that provides a meaningful neuromuscular stimulus (Bullo et al., 2018; Muollo et al., 2019; Morano et al., 2024).

In contrast, with regard to the upper limb, our findings are more in line with those of NW interventions, in which handgrip strength does not show substantial pre–post changes, with values remaining essentially stable despite improvements in other functional outcomes (Grigoletto et al., 2022; Du et al., 2025). At the same time, other studies, such as Morano et al. (2024), have reported clear pre–post gains in handgrip strength following NW training, suggesting that upper-limb adaptations may depend on specific characteristics of the training dose, duration, and exercise content. In our sample, BCS were slightly stronger than HW at all three time points for both hands. On the right side, BCS consistently outperformed HW, and the difference between the two groups remained relatively stable throughout the intervention. On the left side, BCS displayed higher values at baseline and T1, whereas HW partially closed the gap by T2. Descriptive data suggested a transient increase in grip strength at T1 in BCS on both sides, followed by a return to baseline levels at T2, while HW showed a more gradual improvement on both hands. Similarly, in models restricted to BCS, handgrip performance did not differ according to the side of cancer localization. Taken together, these findings may be

viewed in the context of previous work, which has underlined that heterogeneity in testing protocols and in the summary measures used for handgrip can affect the precision and reproducibility of the assessment and complicate comparisons of absolute values across different study populations (Roberts et al., 2011b; Labott et al., 2019). Indeed, in the present study, two different equipment have been used for BCA and HW. The results may also suggest that, in this cohort, the 8-week NW program, delivered twice a week and primarily focused on technique learning, may have been insufficient in terms of duration, intensity, and/or specificity to elicit a robust improvement in maximal isometric handgrip strength. Overall, the handgrip strength values observed in our sample appear to fall within the ranges reported in recent international normative data for adults of comparable age and sex (Tomkinson et al., 2025).

Going to the flexibility outcomes, the sit-and-reach performance revealed a significant difference, with BCS consistently showing higher flexibility than HW across all assessments, but with no change over time, indicating that the 8-week program did not meaningfully influence hamstring and lower-back flexibility in either group. Throughout the intervention period, the difference between BCS and HW remained essentially unchanged. By contrast, back scratch performance improved over time on both the right and left side in both groups, suggesting that shoulder flexibility increased in a similar way in BCS and HW. Among all these kinesiological outcomes, the only one that diverges from previous literature is the sit-and-reach performance, which in the present study did not show any appreciable improvement, in contrast with the gains in flexibility reported by previous NW interventions (Kawamura et al., 2018).

Consistent with the improvements in upper-limb flexibility, ROM assessments also demonstrated increased shoulder mobility throughout the intervention. Shoulder ROM increased over time across all four movements in both groups and on both the dominant and non-dominant sides. At the same time, some consistent differences between groups emerged. HW tended to show slightly greater flexion and abduction ROM than BCS at all assessments, whereas adduction ROM was

similar between groups. For extension, BCS and HW appeared to follow somewhat different adaptation patterns, but both groups reached comparable values by T2. Overall, these between-group differences were small relative to the absolute gains achieved over time and did not prevent either group from improving shoulder ROM. These gains indicate that the 8-week NW program provided an effective stimulus to enhance shoulder mobility, aligned with the findings in other literature on upper body flexibility (Fischer, Krol-Warmerdam, Ranke, Vermeulen, Van Der Heijden, et al., 2015; Kocur et al., 2017).

Moving toward the static balance assessment, both groups showed a reduction in sway area over time. This pattern suggests a modest improvement in static postural stability over the 8-week NW program, with similar overall changes in BCS and HW; descriptively, the decrease in sway area tended to be slightly larger in HW. A similar picture emerged for sway path length, with an overall reduction across the intervention in both groups. In this case, HW appeared to improve more than BCS, showing a more marked shortening of the sway length over time. Importantly, BCS did not show any deterioration in static balance; instead, their sway measures also evolved in a favourable direction, albeit to a somewhat lesser extent. To our knowledge, no previous investigation has specifically quantified the outcome of NW intervention on static balance in BCS. However, studies conducted in other populations, particularly older adults, have reported beneficial effects of NW on static postural stability (Gomeñuka et al., 2019), and, similarly, there are studies in breast cancer survivors that have shown that exercise-based interventions in general can improve static postural balance (Bula et al., 2023). Although exploratory, the median-based stratification of participants according to sway area measured at baseline yielded some additional and potentially interesting insights into the static balance data. Using a median split of the values on the area of body sway at T0, we identified two subgroups: one with relatively better static balance (below-median sway area) and the other with poorer static balance (above-median sway area). Focusing first on women classified as having poorer static balance at baseline (above-median sway area), sway area showed a clear reduction over time in both

groups. In this subgroup, the area decreased from T0 to T2, indicating an improvement in static postural stability. Among women who already exhibited relatively good static balance at baseline (below-median sway area), sway area generally remained low over the 8-week NW program, with no clear overall change across time. However, the two groups followed different trajectories: HW tended to show small further reductions in sway area, whereas BCS displayed a noticeable increase in sway area. Importantly, though, mean sway area values in BCS remained below the original median split threshold at all time points, indicating that this apparent worsening occurred within a range still compatible with relatively good static balance. Overall, this median-based approach should be viewed as an exploratory analysis. Nevertheless, these findings may point to a potentially meaningful differential responsiveness to NW according to baseline balance status, which would be worth investigating in future studies.

4.5 Conclusion

To conclude, the present results may suggest a partial and differentiated adaptation to the NW program, rather than a uniform whole-body effect as we hypothesized. Lower-limb and trunk strength improved, whereas grip strength did not show a clear training-related increase, but a possible explanation is that this pattern may be driven less by the specific side of cancer involvement and more by the nature of NW itself, which does not provide a true maximal strength stimulus; as a result, it may enhance strength when assessed through repeated functional tasks but not necessarily when measured as maximal handgrip force. However, in addition to the aspects already discussed above, it should also be acknowledged that a limitation of the handgrip outcome is that measurements were obtained using two different instruments, despite standardized procedures, which may have influenced the results. Similarly, shoulder flexibility improved over time in both groups, while hamstring and lower-back flexibility remained unchanged. The only outcome that really diverged from our initial expectations was the sit-and-reach result, in which the lack of improvement in performance, particularly in BCS, may at least partly

reflect the relatively high baseline flexibility levels observed in this group, which could have limited the potential for further gains.

Finally, it should be acknowledged that the present intervention was primarily designed as a technique-learning program rather than a cardiovascular conditioning protocol. The first eight sessions typically involved low-impact, technique-oriented practice that was not expected to elicit substantial cardiovascular adaptations; therefore, we did not systematically assess cardiorespiratory outcomes.

But overall, we believe that these findings support the view of NW as a myofascial-oriented, multicomponent discipline capable of stimulating different body segments (Morano et al., 2024), but at the same time, we underscore the need to further investigate how different NW training protocols can affect neuromuscular, flexibility, and functional outcomes in both clinical and non-clinical populations. A more systematic understanding of these dose–response relationships would help refine NW-based exercise prescriptions and expand the range of evidence-based options available for preventive and rehabilitative programs.

5 COMPANY-BASED PROJECT

Another aim of this doctoral work was to formulate suggestions for optimizing accessibility and provide targeted advice and ideas to enhance the dedicated app and service portal, aiming to ensure a clearer user journey and a more comprehensive overall experience for users and physical activity professionals working with NW across various areas of use.

Our initial objective was to test the accuracy of the pole-recorded data by benchmarking selected recordings against an optical motion-capture system, widely regarded as the gold standard for such measurements. To this end, we conducted a series of laboratory tests with two instrumented pole configurations: one with an accelerometer-based pole and the other with a pole with an inertial measurement unit (IMU). Each configuration was synchronized with motion capture to quantify precision and test–retest reliability. Then, in collaboration with a team of computer scientists, these datasets were used to improve the accuracy of the pole-derived outputs. Based on the comparative results, the company decided to adopt the accelerometer-based design for the NW application, while continuing development of the IMU-based prototype for future projects, including cross-country skiing. After completing this step, most of the subsequent work concentrated on the motor domain of NW, which had already been examined in the preceding chapters. However, in parallel, we advanced the E-Poles ecosystem by enabling two guided functional tests.

In detail, it is now possible, directly under in-app guidance, to perform two distinct functional tests: the Six-Minute Walk Test (6MWT) and the 1-Mile Walk Test. The application provides all the necessary instructions to perform the test, which can therefore be carried out independently or in conjunction with an exercise science professional interested in conducting scientifically grounded assessments of subjects/clients.

The 6MWT **(Fig. 1)** and the 1-mile walk **(Fig. 2)** were integrated because they are standardized, low-cost, and safe field protocols widely used to quantify functional capacity and cardiorespiratory fitness. (Enright & Sherrill, 1998; Gibbons et al., 2001, p. 1; Kline et al., 1987)

In the app, both tests are intended to be performed walking, not as NW, since no established NW-specific reference values or prediction equations are currently available. This choice ensures that results can be compared against existing normative data for walking. Importantly, repeating the same walking test under consistent conditions remains useful for detecting individual trends after a period of NW training, providing a clear indication of improvement or decline. However, it is essential to recognize that these outcomes are intra-subject comparisons and not NW-specific normative scores.

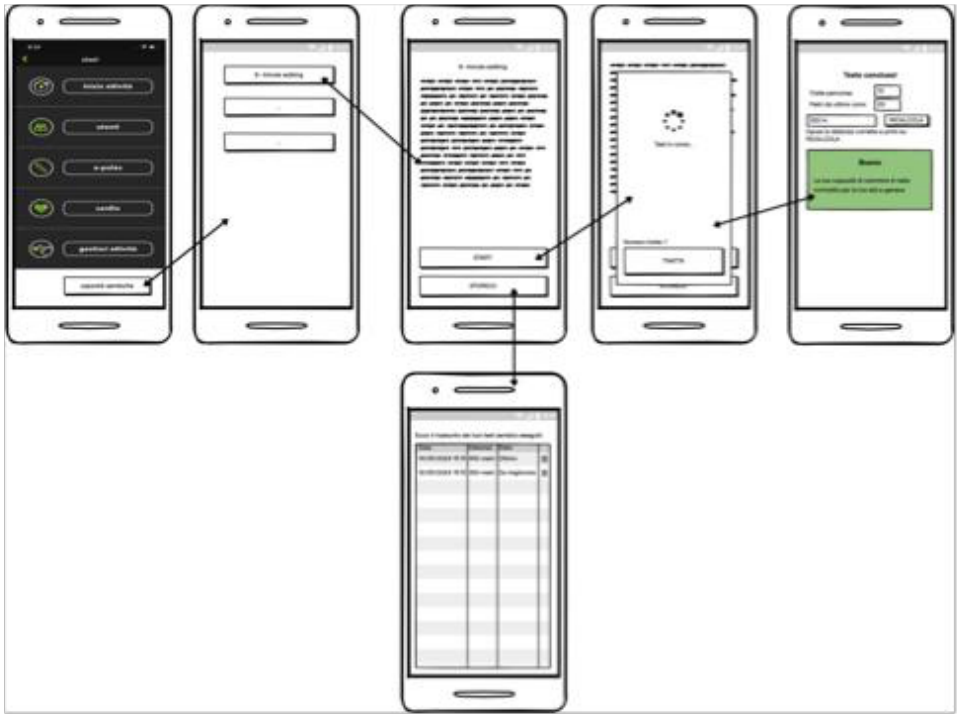

Fig. 1. The six-meter walking test screen from the E-Poles App.

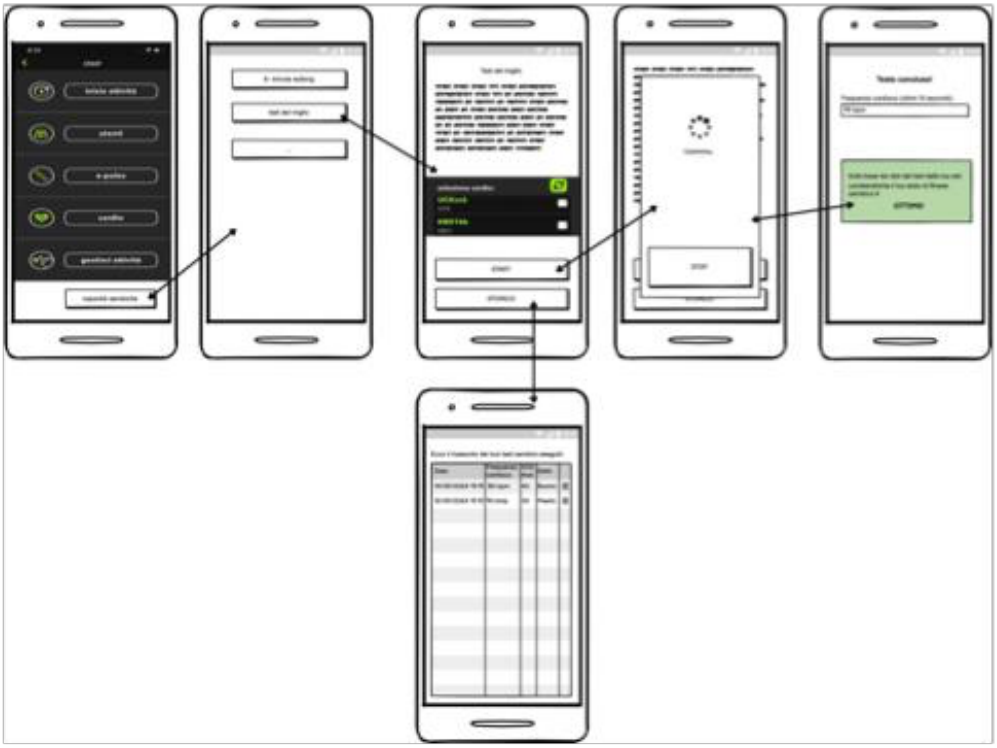

Fig. 2. The 1-mile test screen from the E-Poles App.

Moreover, normative reference values have been added for selected pole-derived parameters, based on data collected from the work described in the preceding sections. These values are integrated into the application **(Fig. 3)**, which now provides immediate post-recording feedback. To be specific, the parameters are:

- **Right pole contact duration (T06):**

T06 ≥ 40% → right pole contact time within the recommended range.

T06 < 40% → right pole contact time below the suggested range; try to increase it.

- **Left pole contact duration (T05):**

T05 ≥ 40% → left pole contact time within the recommended range.

T05 < 40% → left pole contact time below the suggested range; try to increase it.

- **Contact symmetry L/R (I03):**

I03 ≥ 86 → good contact symmetry between poles.

80 < I03 < 86 → suboptimal symmetry; aim for more similar contact times.

I03 ≤ 80 → poor symmetry; work on equalizing contact duration between right and left poles.

- **Angle symmetry L/R (I04):**

I04 ≥ 90 → good pole angle symmetry.

84 < I04 < 90 → acceptable but improvable; aim for more similar pole inclination.

I04 ≤ 84 → poor symmetry; adjust technique to reduce differences in pole angle.

From now on, the APP provides technique feedback based on the three metrics.

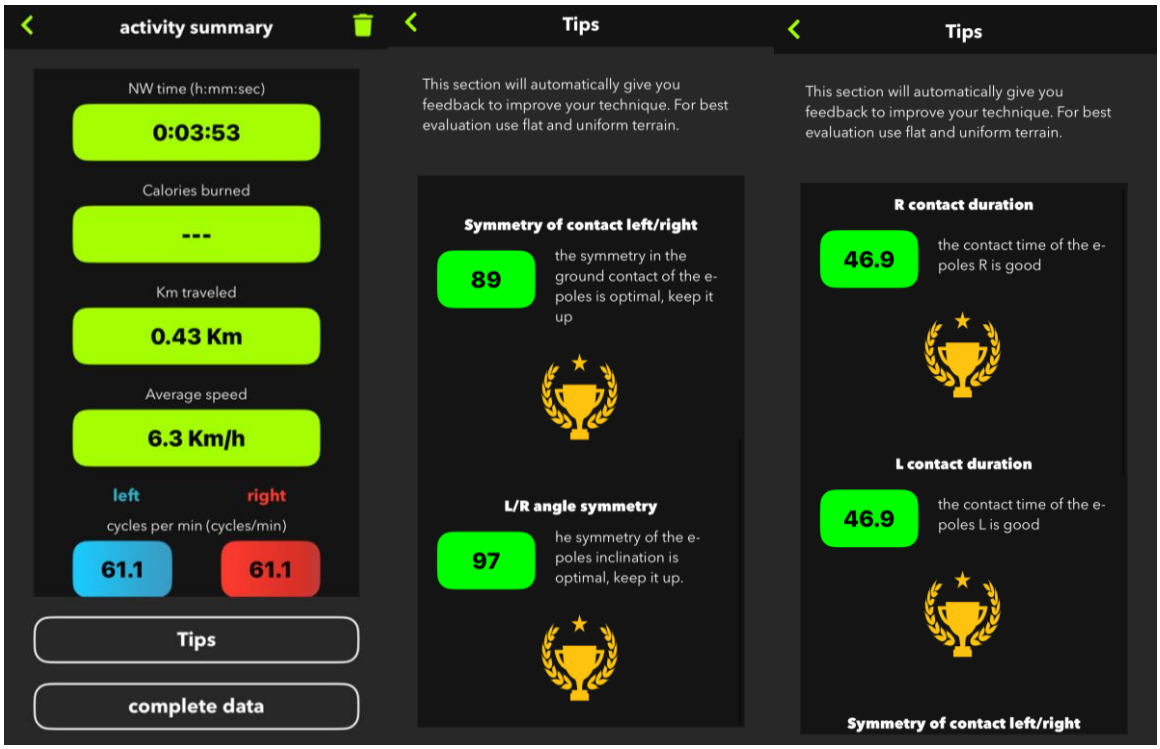

Fig. 3. E-Poles APP: overview of the in-app feedback.

6 PRACTICAL APPLICATIONS AND FUTURE PERSPECTIVES OF THIS DOCTORAL PROJECT

As outlined at the beginning of this project, NW is becoming increasingly popular among healthy individuals as a recreational and sporting activity, and as a form of exercise incorporated into programs aimed at improving health in a wide range of clinical conditions. However, to fully realize its benefits, practitioners need to perform NW as closely as possible to the technique generally considered correct. From this perspective, the present Doctoral thesis provides concrete practical applications, as it (1) evaluates whether pole design can induce changes during NW practice, (2) proposes technological tools and methodologies capable of monitoring these parameters objectively, including real-world environments outside laboratory settings, and (3) identifies the most sensitive biomechanical parameters to describe NW technique quality. The integration of sensors into the poles, along with dedicated in-app feedback, enables instructors and health professionals to quickly assess technique, personalize exercise prescriptions, and track changes in these parameters over time. At the same time, users can receive immediate guidance to adjust their technique, thereby increasing safety, training effectiveness, and adherence to programs.

Looking ahead, a natural next step is to apply the E-poles system to other conditions that are responsive to NW, where sensorized poles could support individualized exercise prescription and enable objective monitoring of changes over time. In particular, this approach appears relevant for neurodegenerative disorders such as Parkinson's disease, where NW has already shown promising effects (Cugusi et al., 2015, 2017; Bombieri et al., 2017; Salse-Batán et al., 2022) and where technology-assisted delivery may improve standardization and follow-up.

Importantly, future applications should move beyond the monitoring of traditional aerobic-capacity outcomes, as widely documented for NW, and increasingly focus on biomechanical and coordinative parameters derived from the E-Poles (e.g., pole angle and timing, pace regularity, inter-limb coordination and symmetry), in order to quantify technique quality and detect subtle, clinically meaningful changes over time in real-world settings.

Within Parkinson's disease specifically, repeated recordings of these metrics could be explored as potential digital markers of functional deterioration and variability across disease stages; prospective studies should therefore test feasibility and adherence, establish clinical validity and sensitivity to change against standard clinical scales and functional tests, and examine whether these patterns differ systematically across medication ON/OFF windows. This direction aligns with the broader shift toward objective, sensor-based monitoring in Parkinson's disease, including approaches used to characterize motor fluctuations and to inform medication adjustments (Moreau et al., 2023; Packer et al., 2025; Rodríguez-Molinero et al., 2025). Furthermore, unlike the BCS cohort examined in this thesis, whose motor deficits are primarily related to upper-limb dysfunction, Parkinson's disease is also characterized by gait impairments, including reduced stride length and decreased gait fluidity. Accordingly, different e-pole parameters should be prioritized, such as cycles per minute, and disease-specific metrics may need to be developed to adequately capture these distinct motor signatures. Notably, motor impairment in Parkinson's disease is markedly asymmetric, as the disease begins and progresses unilaterally before becoming bilateral. This lateralized pattern suggests that E-pole metrics such as L/R contact symmetry and L/R pace regularity may be particularly informative, as they are specifically designed to capture inter-limb asymmetries during NW, a dimension that, despite the relevant anatomical and neurological differences, is shared with the BCS examined in this thesis, and with other clinical population such as people affected by stroke, which represents another clinical condition in which NW and E-Poles-based monitoring may offer relevant insights (Kang et al., 2016; Magalhães Demartino et al., 2023).

As with Parkinson's disease, post-stroke motor impairment affects gait, balance, and interlimb coordination, making sensor-derived metrics a potentially valuable tool for both rehabilitation monitoring and functional assessment. However, the current literature on NW in stroke rehabilitation remains limited, representing a potential gap and an interesting avenue for future research.

In relation to the lateralized nature of motor impairment, a further emerging population of interest can be represented by children with hemiparesis, where gait asymmetry is a defining feature of the condition. A very recent RCT demonstrated the efficacy of NW compared to conventional gait training in improving asymmetric gait patterns in this population (Nashed et al., 2026), suggesting that the bilateral, coordinated nature of NW, and the inter-limb symmetry metrics provided by sensorized poles, may be particularly well-suited to address lateralized motor impairment across different clinical contexts and age groups.

Finally, in light of recent advances in artificial intelligence, a promising future direction would be the development of personalized feedback algorithms integrated into the E-Poles system, capable of adapting technical feedback to individual characteristics such as age, fitness level, and clinical condition. The data collected from the two populations involved in the present study could represent a valuable foundation for developing such differentiated learning profiles, potentially enhancing the system's applicability and effectiveness across diverse clinical and non-clinical contexts.

7 OVERALL LIMITATIONS

First, the analyses on the different pole designs were conducted on a limited number of poles; therefore, the findings cannot be automatically generalized to the wide range of Nordic Walking poles currently available on the market. Future research should include additional designs with different structural features and test them in larger and more diverse samples to strengthen external validity. In study 2, the sample size of 59 women, although adequate for detecting moderate within-group changes, limits the statistical power to identify more minor effects and higher-order interactions, so some potentially meaningful differences may have remained undetected. In Study 3, the intervention did not follow a fully randomized controlled trial design, as participants were not randomly allocated to alternative interventions or a non-exercising control group; therefore, future work should adopt an actual RCT structure to strengthen causal inference. Moreover, sensorized poles are currently more expensive than standard equipment, it may be difficult for individual instructors or small private organizations to maintain enough devices to run group-based sessions. In contrast, they may be more realistically implemented within a hospital or rehabilitation clinic, public health programs, or even a health research center, where resources are centralized, and the potential reach is broader. And, should be noted, however, that the additional cost of training qualified instructors in the use of sensorized poles may not be substantially higher than standard Nordic Walking instructor training, given the relatively straightforward nature of the system; the necessary competencies could potentially be integrated into existing Nordic Walking instructor certification programs. Regardless, it is our view that sessions should always be led by professionals holding at least a degree in Sport Science.

In addition, longitudinal follow-up studies are needed to determine whether technical improvements remain stable over time or whether periodic refresher sessions are required to maintain correct gesture execution.

Lastly, future studies should include truly autonomous NW sessions, in which participants practice independently while receiving remote feedback, following a period of introduction to NW with supervised lessons, to assess the real-world feasibility and scalability of this technology-assisted approach.

8 GENERAL CONCLUSION

Overall, this PhD contributes to clarifying how technical quality in Nordic Walking is a key prerequisite for achieving its expected benefits, both in recreational/sport settings and in clinically oriented exercise programs. The findings suggest that pole design may influence specific aspects of the gesture, including its temporal and joint organization, indicating that equipment choice is not neutral with respect to technique. In parallel, this project identified highly sensitive biomechanical parameters to describe gesture quality, providing an objective basis for more standardized and comparable assessments. Within this framework, the adoption of sensor-equipped poles and app-based feedback represents a relevant practical step: it enables technique evaluation outside the laboratory, supporting instructors and healthcare professionals in tailoring exercise prescription and tracking progress over time. Across the three studies, the results also confirm that NW is an effective and well-suited exercise modality for enhancing functional capacity, balance, and mobility in preventive and rehabilitative settings. A particularly meaningful outcome concerns adherence and the acceptability of practice.

The collected evidence suggests that tools delivering immediate and understandable feedback enhance user engagement, increase perceived safety and perceived usefulness of exercise, and ultimately support long-term participation. This point is especially critical in healthcare contexts, where adherence to exercise protocols directly affects the effectiveness of interventions. Taken together, this work provides both a scientific rationale and operational solutions for a more measurable, personalized, and sustainable Nordic Walking practice, paving the way for real-world applications in prevention, rehabilitation, and health promotion.

In conclusion, the approach proposed in this thesis contributes to reframing Nordic Walking not only as an aerobic exercise modality, but also as a complex motor behavior whose quality can be objectively quantified through wearable sensor technologies.

9 APPENDIX A – PRELIMINARY VALIDATION OF THE E-POLES

To provide a preliminary assessment of the E-Poles system, a single Nordic Walking instructor certified by ANWI performed a standardized NW trial on a treadmill at three different velocities, 4, 5, and 6 $km \cdot h^{-1}$. Sessions were simultaneously recorded using a lateral video camera (100 Hz, 1920 × 1080 pixels) and analyzed with Kinovea (version 0.9.5). Video recordings were frame-by-frame inspected to identify pole contact and release events. For each condition, values were calculated over 15 consecutive gait cycles.

E-Poles data were recorded over a 1-minute trial and represent averaged values automatically provided by the system.

Values for cycle time, pole contact time, placement angle, and uplift angle were compared between the two systems, as these represent the primary kinematic parameters directly measurable by both methods. The remaining parameters provided by the E-Poles software are derived indices calculated through proprietary algorithms by the manufacturer, whose computational details are not publicly available. Independent verification of these parameters against external reference systems was therefore not feasible within the scope of the present study.

Results are summarized in Table A1. Absolute percentage differences between the two systems ranged up to approximately 14%, indicating acceptable agreement between the E-Poles system and video analysis data. In addition, scatter plots (Fig. A1) were generated for each parameter to visually assess the agreement between E-Poles and video analysis across the three walking speeds, with the identity line (y = x) included as a reference.

These findings provide preliminary support for the use of the E-Poles system in field-based assessments.

	4 km·h⁻¹			5 km·h⁻¹			6 km·h⁻¹		
	E-poles	**Video analysis**	**Difference %**	**E-poles**	**Video analysis**	**Difference %**	**E-poles**	**Video analysis**	**Difference %**
Parameters									
Cycle time (s)	1.4	1.34±0.05	4.4	1.2	1.16±0.02	3.4	1.1	1.11±0.04	0.9
Pole contact time (s)	0.7	0.71±0.05	1.4	0.6	0.61±0.04	1.6	0.6	0.53±0.03	13.2
Placement angle (°)	50.2	53.14±0.61	5.5	47.3	48.6±0.64	2.6	46	47.8±1.22	3.7
Uplift angle (°)	47.2	45.7±0.87	3.2	46.2	46.9±0.8	1.4	45.5	44.3±0.90	2.7

Table A1. Comparison of the NW temporal and pole-related kinematic parameters derived from E-Poles and video analysis. The difference % column shows the percentage difference between values measured by the E-Poles system and those obtained from video analysis.

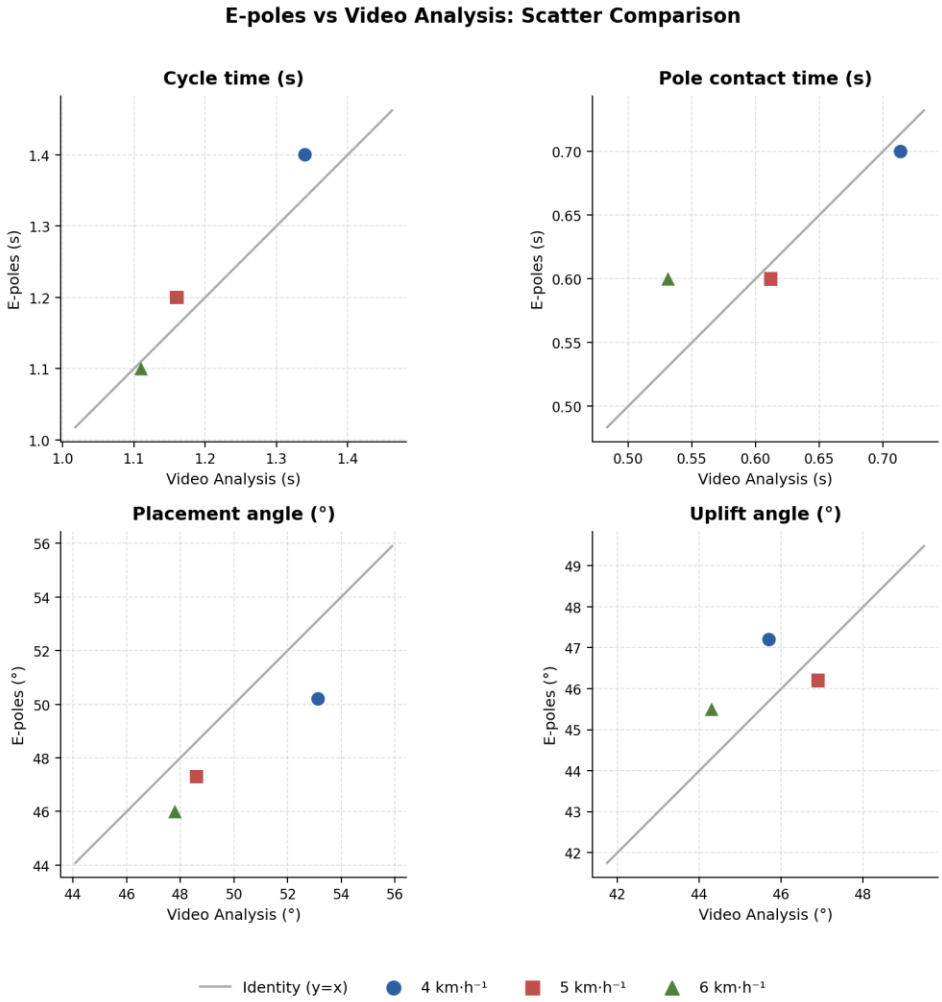

Fig. A1. Scatter plots comparing E-poles and video analysis measurements across three walking speeds (4, 5, and 6 km·h⁻¹) for cycle time (s), pole contact time (s), placement angle (°), and uplift angle (°). The grey line represents the identity line (y = x). Data points above the line indicate overestimation by the e-poles system; data points below indicate underestimation.

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Ed eccoci nell'unica pagina che, forse, qualcuno avrà la curiosità di leggere senza essere stato gravato da compiti di tutoraggio o revisione. Per prima cosa mi preme dire che se sono riuscito a scriverla, vuol dire che è finita e non era affatto scontato! Ma andiamo dritti al punto per cui siete qui.

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Voglio concludere dedicando questo traguardo a mio zio, Riccardo, ogni buon Samurai avanza ogni giorno dopo giorno, oggi più abile di ieri, domani più abile di oggi. L'addestramento non finisce mai! 花は桜木、人は武士

Ed infine, as usual, che la Forza sia con voi, perché già scorre potente in me!

G.

STATEMENT ON ORIGINALITY AND USE OF AI TOOLS

All content, ideas, and analyses presented in this thesis are original. ChatGPT (Free Web version) was used for grammar checking and stylistic refinement. All AI-assisted revisions were subsequently reviewed to ensure that the original meaning was preserved.

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