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Advancements in Non-Invasive Screening Techniques for Human Posture and Musculoskeletal Disorders

Ph.D. Student
FEDERICO ROGGIO

Ph.D. Coordinator
Professor GIUSEPPA CAPPUCCIO

Supervisor
Professor ANTONIO PALMA

Co-Supervisor
Professor GIUSEPPE MUSUMECI

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Introduction

Musculoskeletal disorders (MSDs) are a prevalent global health concern, significantly impacting the quality of life across various age groups. These conditions, characterized by pain and functional impairment, pose a substantial burden on healthcare systems and individual well-being. The traditional diagnostic approaches, often invasive and resource-intensive, have limitations in early detection and management, particularly among adolescents and young adults (AYAs). This demographic is increasingly at risk due to lifestyle and ergonomic factors yet remains underrepresented in MSD research and intervention strategies. The necessity for non-invasive, accessible, and cost-effective screening methods is crucial, highlighting a gap in current medical practices and public health initiatives.

Research gap

Existing literature primarily focuses on the treatment and management of advanced stages of MSDs, with less emphasis on early detection and non-invasive management strategies. This oversight is particularly evident in the context of AYAs, a group that often does not receive timely intervention due to the subtle onset and progression of these disorders. The lack of comprehensive and accessible screening programs contributes to delayed diagnosis and treatment, exacerbating the long-term impact of MSDs.

Aim of the thesis

This research aims to explore the efficacy and practicality of innovative, non-invasive screening methods for early detection and management of musculoskeletal disorders in adolescents and young adults. By integrating thermography, 3D imaging, and photo-analysis, the study endeavors to offer a comprehensive understanding of their potential in identifying early signs of MSDs. This approach is expected to bridge the significant gap in early screening, providing a proactive strategy in managing these disorders.

Research methodology

The study utilizes a mixed-methods approach, employing non-invasive techniques such as thermography, 3D imaging, photographic analysis, and machine learning models. The target population comprises adolescents and young adults, with a focus on early detection of MSDs. Data collection involved qualitative and quantitative methods, including surveys, interviews, and physical assessments. The analysis integrated statistical techniques to evaluate the effectiveness of the screening methods, alongside machine learning methodologies to thoroughly explore the data. The thesis summarizes the research path, emphasizing the diverse methodologies employed during the PhD course and the potential insights these methods offer across various research fields, as outlined in Table 1.

Year	Title	Summary
2021	*One year of COVID-19 pandemic in Italy: effect of sedentary behavior on physical activity levels and musculoskeletal pain among university students*	Investigate changes in physical activity levels among Italian university students before and during the COVID-19 pandemic. Furthermore, explore the relationship between sedentary behavior and musculoskeletal pain and how this impacted pain and fatigue as they relate to daily life activities.
2021	*Technological advancements in the analysis of human motion and posture management through digital devices*	Provide a comprehensive review of the latest technological advancements in the analysis of human motion and posture, focusing on how these innovations are transforming rehabilitation, sports, and clinical assessment practices.
2023	*Thermography and rasterstereography as a combined infrared method to assess the posture of healthy individuals*	Investigate the potential of combining rasterstereography and infrared thermography as a new noninvasive approach for assessing posture in healthy individuals.
2023	*Thermal profile classification of the back of sportive and sedentary healthy individuals*	Investigate differences in the thermal profiles of the back between healthy individuals who are sedentary and those who engage in various sports.
2023	*Infrared Thermography for the Evaluation of Adolescent and Juvenile Idiopathic Scoliosis: A Systematic Review*	Systematically review existing research on the use of infrared thermography for evaluating adolescent and juvenile idiopathic scoliosis and assess its potential as a non-invasive, radiation-free tool for detecting muscle changes and thermal differences associated with scoliosis.
2022	*Kinesiological Treatment of Early Spine Osteoarthritis in a Motorcyclist*	A case study investigating the potential link between prolonged vibrations from enduro motorcycle riding and early-onset spinal osteoarthritis assessed with rasterstereography and underwent a kinesiological treatment.
2022	*Running Footwear and Impact Peak Differences in Recreational Runners*	Explore differences in running biomechanics between recreational runners who exhibit an impact peak during their stride and those who don't. Furthermore, investigate the potential connections between impact peaks and other biomechanical aspects of running.

2022	*Postural Evaluation in Young Healthy Adults through a Digital and Reproducible Method*	Evaluate the use of a mobile app for the posture analysis (APECS) for digital postural assessment in healthy young adults. It aimed to establish normative data for young adults using this app, providing a benchmark for future comparisons.
2022	*Ergonomic evaluation of young agricultural operators using handle equipment through electromyography and vibrations analysis between the fingers*	Investigate the ergonomic risks associated with using handle equipment (brushcutter, electric saw, hedge trimmer) in young agricultural workers and assess the impact of these tools on both muscle activity and working posture, highlighting potential health issues.
2022	*Exploiting Real-World Data To Monitor Physical Activity In Patients With Osteoarthritis: The Opportunity Of Digital Epidemiology*	Explore the potential of digital technologies (wearables, smartphones) and the concept of digital epidemiology in revolutionizing how we monitor and promote physical activity in patients with osteoarthritis.
2023	*Assessing Body Posture with Artificial Intelligence: Applicability and Reliability in Healthy Adult Population*	Investigate the use a machine learning pose estimation mode, for analyzing human posture in a healthy population. Focus on the technology's potential for accurate, efficient, and reliable posture assessment.

Significance of the study

The anticipated contribution of this research lies in its potential to revolutionize the understanding, diagnosis, and management of MSDs, particularly in AYAs. By offering non-invasive, cost-effective, and accessible screening methods, this study aims to inform public health strategies and preventive health care. The findings could lead to a paradigm shift in early intervention approaches, reducing the long-term impact of MSDs and enhancing the quality of life for individuals at risk.

Conclusion

This thesis represents a significant contribution to the field of musculoskeletal disorder research, particularly in the context of early detection and non-invasive management. By bridging the gap in current screening practices, it offers a new perspective on preventive health strategies and contributes to the overall improvement of public health outcomes for adolescents and young adults.

Chapter 1

The role of primary screening for the prevention of musculoskeletal disorders

1.1 Introduction

In recent years, the prevalence and impact of musculoskeletal disorders (MSDs) have garnered increasing attention in medical research and public health discourse. Despite this growing awareness, there remains a significant gap in our understanding of MSDs, particularly in their early detection and non-invasive management. This thesis investigates the efficacy and practicality of non-invasive screening methods, including thermography, 3D imaging, and photo-analysis, in the early detection and management of MSDs among adolescents and young adults (AYAs). It aims to bridge the gap in early MSD screening and provide innovative solutions that are accessible, cost-effective, and patient-friendly. Traditional diagnostic and treatment approaches often rely on invasive, costly, and time-consuming methods that may not be suitable or accessible for all populations or for providing widespread screening programs. By investigating new alternative techniques such as thermography, 3D cameras, and photo-analysis, this study seeks to contribute to a more comprehensive, accessible, and effective approach to MSD management. The focus on adolescents and young adults (AYAs) is particularly pertinent, given the rising incidence of MSDs in this demographic and the long-term implications for their health and well-being. The novel methodologies explored in this thesis have the potential to offer a fresh perspective on how we understand, diagnose, and manage MSDs, making a significant contribution to the field and offering new alternatives for patient care and preventive health strategies.

A search on PubMed using the keywords 'prevention of musculoskeletal disorders' yields approximately 109,000 articles, highlighting the widespread focus on preventive methods for these conditions, particularly in various workplace environments. MSDs generally refer to alterations of the soft tissues that arise from a prolonged exposure to repetitive movements, forces, vibrations, or awkward postures [1]. They encompass a broad spectrum of conditions affecting the locomotor system, including muscles, bones, joints, and tendons. Notable examples include rheumatoid arthritis, osteoarthritis, low back pain, neck pain, and gout. These disorders typically manifest as joint pain, stiffness, and decreased mobility, potentially leading to physical impairment, depressive symptoms, and an increased risk of chronic conditions like cardiovascular disease [2]. They represent a global burden that is challenging to address, as unlike other diseases, they lack a clear pathological definition and diagnostic picture. The incidence of this condition affects many realities; from the work-related MSDs such healthcare or office workers, to the incidence related to ageing, sedentariness and reduced physical activity.

1.2 Global burden of musculoskeletal disorders among young adults

MSDs are a primary cause of disability, ranking highest in years lived with disability and sixth in disability-adjusted life-years as of 2019 [3]. Their chronic and progressive nature places a substantial strain on healthcare systems and financial resources [4]. Adolescents and young adults (AYAs), defined as those aged 15–39 years, represent a population experiencing significant physical, emotional, and psychosocial changes. This life stage, marked by important life events like career development, higher education, and family formation, is critical. However, MSDs are the leading causes of work-related absenteeism, reduced productivity, and early retirement among this age group, significantly impacting the economy [5]. AYAs often encounter barriers in accessing adequate healthcare, timely diagnosis, and effective treatment for MSDs, leading to disparities in care. This latency can result in prolonged disease exposure and higher risks of chronic complications, including posture alterations and chronic pain. Despite these issues, research on MSDs predominantly targets the elderly, often neglecting the distinct epidemiological trends, healthcare needs, and societal impacts on AYAs. Due to the lack of attention paid to this population, this condition also elevates the likelihood of increased risk for persistent pain and opioid abuse in adulthood [6]. Experiencing MSDs during youth is a risk factor for chronic pain conditions in adulthood [7]. Having MSDs greatly impairs physical functionality, often coincides with mental health challenges, and leads to increased healthcare expenses [8]. Consequently, it is imperative to shift the focus of healthcare from solely curative to more encompassing approaches, including preventive, promotive, and rehabilitative strategies. Shifting focus could counter the tendency towards over-medicalization and a predominantly biomedical approach. In contrast, a more comprehensive biopsychosocial perspective may prevent suboptimal or negative health outcomes and unsustainable healthcare costs [9].

In order to estimate the incidence of MSDs among AYAs, it is mandatory to refer to 'The Global Burden of Disease (GBD)' which is a study offering a comprehensive overview of mortality and disability across different countries, ages, and sexes over time [10]. It quantifies health loss from hundreds of diseases, injuries, and risk factors, aiming to improve health systems. The study provides detailed insights into global health trends, challenges, and global health issues. Recently, Shi-Yang et al. [11] published an analysis of the GBD results, focusing on the risk factors of musculoskeletal disorders among AYAs. In 2019, there were 87.475.020 new cases, 359.072.781 existing cases, and 39.449.932 disability-adjusted life years (DALYs) among AYAs attributed to MSDs. These accounted for 7.6% of the total DALYs from all causes within this demographic, Figure 1.1.

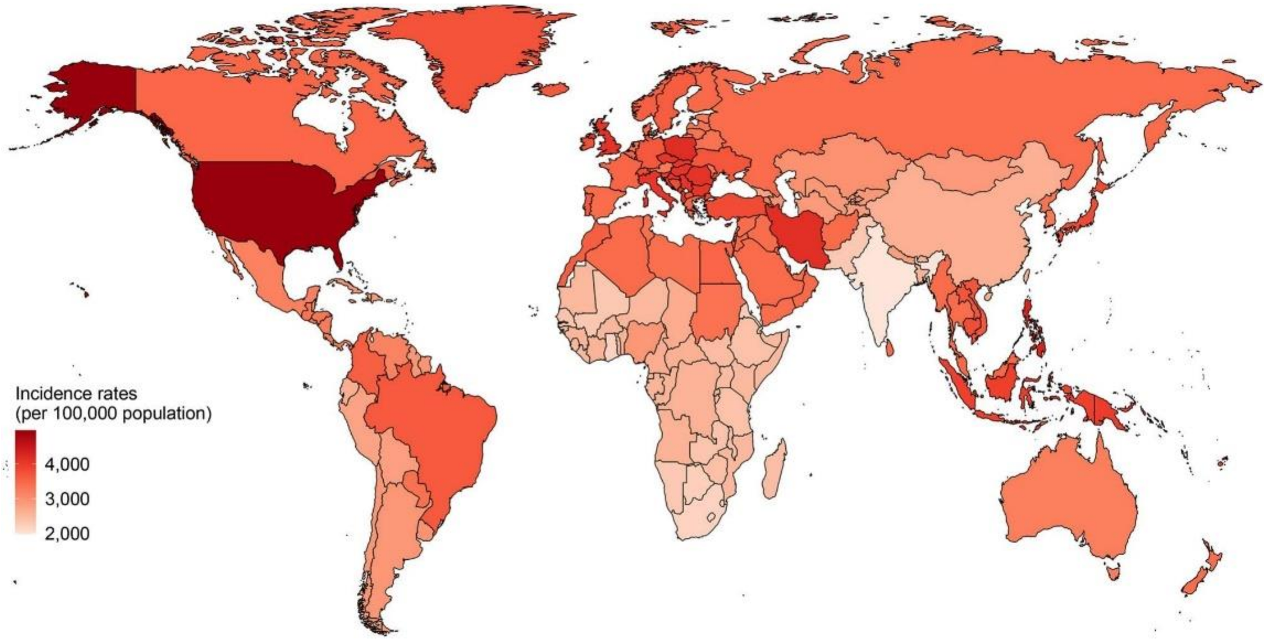
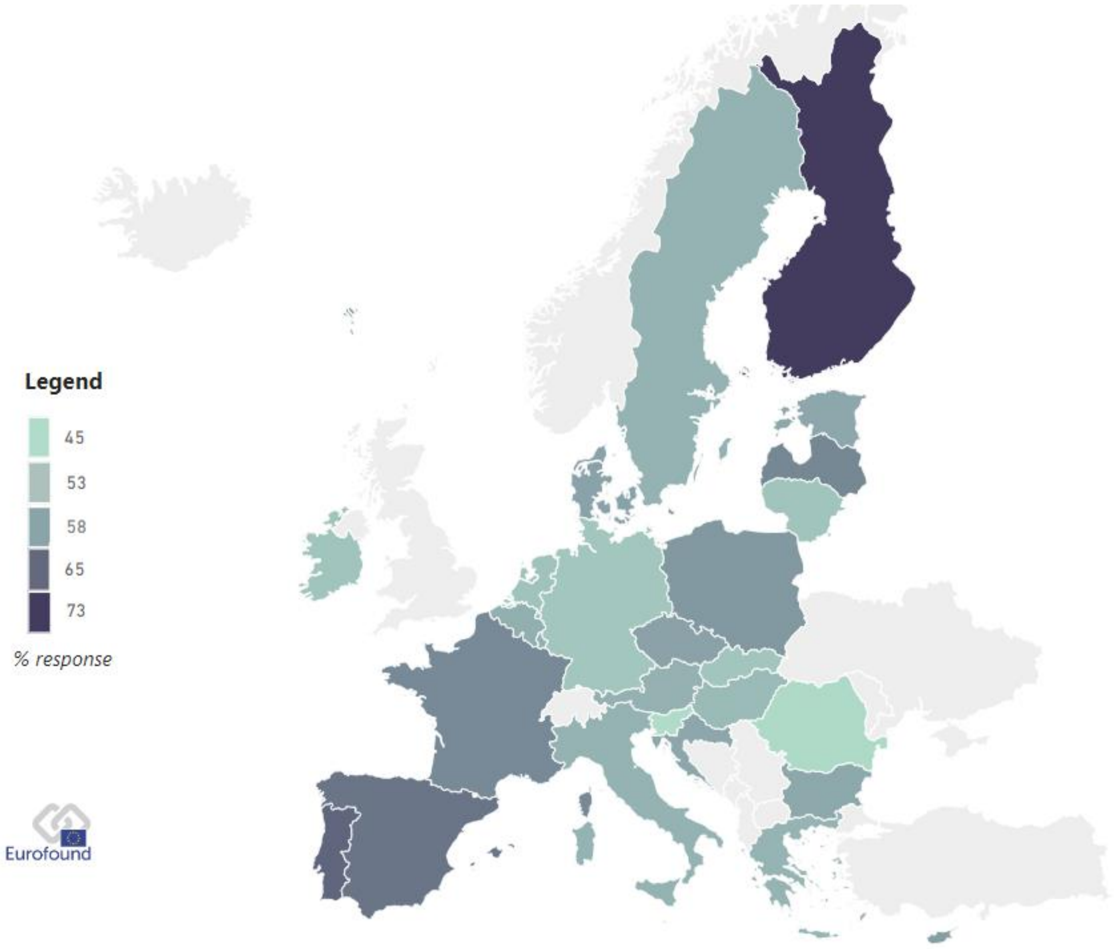


Figure 1.1: *Age standardized incidence rates for MSDs among AYAs in 204 countries and territories in 2019 [11].*

From 1990 to 2019, there has been a significant increase in the global incidence, prevalence, and DALYs of MSDs disorders among AYAs. Specifically, incident cases increased by 21.2%, prevalent cases by 39.3%, and DALYs by 36.2%, emerging as the third global cause leading cause of global DALYs. Within the major categories of causes, MSDs have escalated from the sixth to the third leading cause of global DALYs. Among the MSDs, low back pain was the predominant one MSD among AYAs, comprising 76.4% of new cases, 45.2% of existing cases, and 47.2% of DALYs. Neck pain was the second most common, followed by osteoarthritis, gout, and rheumatoid arthritis and other MSDs. The authors pointed out that over the past 30 years, globally, the proportions of DALYs attributable to occupational ergonomic factors and smoking steadily decreased, while the proportions of DALYs attributable to high BMI increased. Specifically, it has been found that occupational ergonomic factors were the primary contributors to MSK DALYs in AYAs. There has been a global decrease in DALYs due to ergonomic factors and smoking over the past three decades, attributed to technological advancements and reduced smoking rates among youth. However, the study notes a significant global increase in DALYs related to high BMI. Therefore, maintaining individual health and activity is crucial.

1.3 Economic burden of MSDs

The economic burden of MSDs significantly affects the workforce through increased absenteeism, decreased productivity, and elevated costs related to worker compensation and disability management [5]. The European Working Conditions Survey revealed that in 2021, the most commonly reported health problem among workers was upper limb pain (57%), followed by backache (54%), and muscular pains in the hip or lower limbs (35%) [12]. The countries with a percentage of MSDs greater than 60% were Finland (74%), Portugal (68%), Spain (66%), France (63%), and Poland (61%). On the other hand, the countries with a percentage lower than 50% were Romania and Slovenia, 45% both, Figure 1.2.



Source: European Working Conditions Telephone Survey – 2021

Figure 1.2: *European distribution of the MSDs incidence referring to muscular pain in shoulders, neck and upper limbs over the last 12 months. Source: European Working Conditions Telephone Survey – 2021*

Work-related MSDs are the most prevalent work-related health issue in Europe, affecting workers across all sectors and jobs. These disorders not only impact the workers but also result in significant costs for businesses and society. The European Agency for Safety and Health at Work (EU-OSHA) gathers national data on the incidence of MSDs to provide an overarching view across Europe [13]. The prevalence of MSDs is a significant concern in many EU Member States, specifically, back pain and muscular pain in the upper limbs are the most common issues. MSDs not only affect the daily well-being of workers but also have significant economic repercussions. They contribute to productivity loss in the workplace and incur social costs, such as expenses related to sick leave. For instance, in

Finland, medical expenses for MSDs amounted to EUR 63.8 million in 2017; in France, work-related lower back pain led to the loss of 12.2 million workdays, with direct annual costs to companies exceeding EURO 1 billion; in Germany, the Federal Institute for Occupational Safety and Health estimated a production loss of EUR 17.2 billion due to reduced labor productivity from MSDs. Therefore, MSDs indirectly affect the economic productivity, costing employers significantly more than regular sickness absences [14]. MSDs encompass various costs: direct costs (medical expenses, including prevention, treatment, and ongoing care), indirect costs (loss of work output, productivity, and family member earnings), and intangible costs (psychosocial impacts and quality of life reduction) [5].

The inability of a large portion of the working-age population in Europe to work due to illness, even in a favorable economic environment, leads to diminished labor productivity and negatively impacts the competitiveness and efficiency of European businesses [5]. An understanding of the various costs of MSDs, both psychological and economic, underscores the need for strategic interventions focused on prevention and early intervention [14]. By addressing MSDs proactively, there is potential to alleviate not only the physical and psychological burden on individuals but also the financial strain on businesses and national economies. As such, a targeted effort towards enhanced screening, improved workplace ergonomics, and public health education could be pivotal in mitigating the extensive impact of these disorders, ultimately benefiting both individual well-being and economic productivity.

1.4 Health strategies to counter the MSDs

In the Global Action Plan for the Prevention and Control of Noncommunicable Diseases 2013–2020, musculoskeletal health was not initially prioritized within noncommunicable disease management [26]. It was only in 2016 that musculoskeletal health was incorporated as a target in the Action Plan for the Prevention and Control of Noncommunicable Diseases in the WHO European Region [15]. Recently, in the EU4Health programme 2021-2027, provided by the European Commission's Health Strategy, one of the key objectives is to strengthen health systems, with a particular focus on enhancing health data, digital tools, and services [16]. Addressing MSDs effectively requires a multi-level approach which involves the health policies, the workforce and tools, and the individual participation.

The application of innovative and non-invasive methodologies can support a more extensive and effective screening process, potentially reducing the costs associated with unnecessary diagnostic examinations. It is a widely accepted thought that unnecessary repetitive diagnostic imaging examinations can expose patients to additional radiation and place pressures on the financial resources of the healthcare system [17]. Preventive screening programs hold immense potential for reducing healthcare costs, addressing a critical concern in contemporary medical economics. By identifying MSDs at an early stage, these programs can significantly diminish the need for more expensive, invasive treatments that are often required in advanced stages of the disease. Early detection through non-invasive screening not only improves patient outcomes but also leads to a more efficient allocation of healthcare resources [18]. The cost savings stem from several factors: reduced hospital stays, lower necessity for complex surgeries, and decreased reliance on long-term medication management. Moreover, by lessening the burden of chronic diseases, preventive screenings contribute to a decrease in indirect costs associated with lost productivity and work-related disabilities [19]. These economic benefits underscore the importance of integrating such programs into the healthcare system, emphasizing a shift from reactive to proactive medical practices. In the long run, a robust preventive screening framework could lead to substantial financial savings, allowing healthcare systems to reallocate funds to other pressing health needs and research initiatives [5]. Thus, investing in preventive healthcare is not only a medically sound approach but also a financially prudent strategy, paving the way towards a more sustainable healthcare model.

1.5 Impact of COVID-19 on MSDs and distance-based technologies

The COVID-19 pandemic has significantly exacerbated the incidence of MSDs, primarily due to the rise in sedentary behaviors associated with extended lockdowns and remote work, as detailed in the report 'Working conditions in the time of COVID-19: Implications for the future' [12]. This shift toward more sedentary lifestyles has increased the risk of developing postural alterations, often the precursors to more severe and challenging MSDs. Without timely and effective intervention, these alterations can lead to conditions that necessitate costly and invasive treatments. At the same time, the global view of the healthcare system drastically changed after the Covid-19 pandemic. While it was a catastrophic and painful event for the entire world, it also catalyzed the development of alternative healthcare methods to reach populations. Although the world was not prepared to handle such a situation, it initiated a process that might have otherwise remained dormant for many more years. This shift brought about significant changes in the concept of distance-based approaches in both education and healthcare. Researchers delved into new methodologies such as telemedicine [20], home-based rehabilitation programs [21], monitoring physiological parameters of athletes remotely during competitions [22], and remote clinical assessments [23]. In education, it was indispensable for continuity, while in healthcare, it led to innovative alternatives [24]. However, the regular implementation of these distance assessment methods still faces certain challenges [25]. This paradigm shift in healthcare, necessitated by the pandemic, underscores the urgent need for innovative approaches in the diagnosis and management of MSDs, leading directly to the focus of this thesis: the exploration and evaluation of non-invasive screening methods and the investigation of the increasing prevalence of MSDs, particularly highlighting the surge in cases linked to sedentary behaviors following the COVID-19 pandemic.

1.6 The aim of non-invasive screening techniques

The foundation of this thesis is rooted in the principle that 'prevention is better than cure,' a cornerstone of modern healthcare especially relevant in the context of MSDs; however the global steps towards a real prevention of MSDs are relatively young [26]. Despite the existence of effective strategies for managing MSDs, there remains a significant gap in their practical application by health providers, their integration into daily lifestyles by individuals, and their representation in health policies, especially considering the burden of the disease.

In addressing these challenges, this thesis delved into the evaluation of non-invasive screening methods, examining their accuracy, efficiency, and practicality in detecting postural and movement anomalies. This includes an exploration of advanced technologies such as thermography and machine learning models, assessing their potential and suitability for posture analysis. Additionally, the thesis investigates how various lifestyle factors, like work environments and physical activity, contribute to these postural and movement alterations. An important component of this research is the development of normative data, which is essential for advancing the field. By taking a comprehensive and multi-dimensional approach, this thesis aimed to make a substantial contribution to the field of MSD screening and management, underscoring the importance and utility of innovative, non-invasive methods in addressing these disorders.

Chapter 2

Impact of sedentary behavior on musculoskeletal health and technological advancements in musculoskeletal disorders analysis

The recent shift towards increased sedentariness and reduced physical activity, especially pronounced during the COVID-19 pandemic, poses significant challenges for public health, particularly concerning MSDs [27]. This chapter explores the effects of these lifestyle changes on MSDs among AYAs and examines the role of evolving technologies in posture and movement analysis.

In the first trimester of 2021, an online questionnaire was disseminated among AYAs to assess the impact of COVID-19 restrictions on their physical activity levels and musculoskeletal health [28]. We employed a stratified sampling method to ensure diverse demographic representation, capturing a broad range of experiences and perspectives. The questionnaire reached a sample of 2044 individuals, spanning various age groups, genders, and socioeconomic backgrounds. The questionnaire comprised questions related to physical activity levels before and during the pandemic, types of activities engaged in, and any experiences of musculoskeletal pain or discomfort. The findings of this study revealed a noticeable shift towards lower physical activity levels during the pandemic, with a significant increase in reported MSDs. Specifically, the pre-pandemic physical activity levels among participants were categorized as follows: 19.9% none, 30.1% light, 21.5% moderate, and 28.5% high. After a year of enduring pandemic constraints, these figures altered significantly, showing 30.6% of participants as inactive, and 48.1%, 10.9%, and 10.5% continuing with light, moderate, and high levels of activity, respectively. Additionally, there was a notable increase in MSDs, with 43.5% of participants reporting neck pain and 33.5% experiencing low back pain. These results underscore a critical correlation: the reduction in physical activity during the pandemic has led to an escalation in the incidence of MSDs. The data emphasizes the crucial role that regular physical activity plays in maintaining musculoskeletal health, especially during periods of enforced inactivity such as those experienced during the pandemic.

Following the accomplishment of this study, a critical observation emerged: AYAs, despite being generally healthy and lacking specific MSDs, frequently experience musculoskeletal pain. This led to a pivotal question: If AYAs are not a pathological group, as they do not exhibit distinct MSDs and are not seeking clinical intervention, how can we effectively engage with them to prevent their musculoskeletal pain from evolving into MSDs? The second article in this chapter addresses this question. Its objective is to collate and analyze pertinent information in the realm of intervention strategies. It focuses on evaluating the application fields, potential of various systems, and distinguishing features that underline the strengths of each approach in preventing the progression of musculoskeletal pain to MSDs among AYAs.

Over recent decades, the rapid evolution of motion and posture analysis technologies has significantly pushed their application in the fields of orthopedics and sports biomechanics. However, the rise of diverse approaches has underscored the necessity to differentiate between various measurement systems to optimize their application. Our study provides a comprehensive summary of existing motion and posture analysis systems, elucidates their optimal use cases, and suggests appropriate methods for specific scenarios [29]. To date, the gold-standard in motion analysis systems, predominantly utilized in clinical settings, confront challenges such as the complexity involved in marker placement and time-intensive procedures. In response, fully automated, markerless systems are emerging as solutions to these limitations, proving particularly advantageous for biomechanical studies conducted outside traditional laboratory environments. Concurrently, innovative posture analysis techniques are being developed. These are largely driven by the demand for rapid, non-invasive methods capable of delivering accurate results. These technological advancements are notably beneficial for young individuals who experience non-specific musculoskeletal pain and postural issues. This article successfully achieves its objective of delineating these devices and their applications, thereby serving as a practical guide for a diverse audience including researchers, clinicians, orthopedists, physical therapists, and sports coaches. By facilitating early detection of musculoskeletal disorders, this research highlighted the critical role of new technologies in the diagnosis, treatment, and prevention of these conditions.

The advancement of these technologies is not just a technical achievement but has profound implications for the early detection and management of MSDs, particularly in younger populations. The incorporation of these advanced, non-invasive technologies could revolutionize how MSDs are diagnosed and managed, promoting efficient and patient-friendly methods valid to reach a broad spectrum of individuals. The findings from the effect of sedentariness and MSDs, combined with the advancements in motion and posture analysis technologies, underscore the urgent need for innovative approaches in the field. These developments align closely with the objectives of this thesis, which seeks to bridge gaps in early detection and provide effective, non-invasive management strategies for MSDs. By advancing our understanding and application of these technologies, we can significantly improve the health outcomes for AYAs and contribute to a more proactive, preventative healthcare approach.

One year of COVID-19 pandemic in Italy: effect of sedentary behavior on physical activity levels and musculoskeletal pain among university students

Federico Roggio [1,2], Bruno Trovato [2], Silvia Ravalli [2], Michelino Di Rosa [2], Grazia Maugeri [2], Antonino Bianco [2], Antonio Palma [2] and Giuseppe Musumeci [2,4,5]

[1] Department of Psychology, Educational Science and Human Movement, University of Palermo, Via Giovanni Pascoli 6, 90144 Palermo, Italy

[2] Department of Biomedical and Biotechnological Sciences, Human Anatomy and Histology Section, School of Medicine, University of Catania, Via S. Sofia 87, 95123 Catania, Italy

[3] Research Center on Motor Activities (CRAM), University of Catania, 95123 Catania, Italy;

[4] Department of Biology, College of Science and Technology, Temple University, Philadelphia, PA 19122, USA

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Introduction

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), responsible of the coronavirus disease 2019 (COVID-19), has spread worldwide since the first reported case in Wuhan in late December 2019, becoming the primary threat to public health in all countries. Since the World Health Organization (WHO), on March 11, 2020, declared the COVID-19 pandemic, many countries, including Italy, launched public health security plans based on promoting social distancing, wearing anti-infection masks, and lockdown restrictions. These extreme measures changed people's lifestyle; in particular, quarantine caused a reduction in physical activity (PA) levels per week in all different age groups, leading to decreased levels of psychological well-being in Italy [30]. Physical inactivity also plays a crucial role in non-communicable chronic disease, and it is considered responsible for over three million premature deaths worldwide every year [31]. The relationship between quarantine-imposed reduced PA level and musculoskeletal pain (MP) is a topic of growing interest nowadays. Sagát et al. [32] showed how this extreme lifestyle change led to an increase in the prevalence of low and neck pain in Riyadh's population aged 18 to 64. Toprak et al. [33] compared people who stayed home and continued to work during the three-month lockdown of the pandemic in Turkey and found that those who stayed home had increased MP symptoms likely due to lower PA levels.

One of the social categories most affected by restricted mobility and reduced PA levels is students. Students typically spend many hours seated on non-ergonomic chairs, assuming incorrect postures, to carry out their curricular activities, leading to a general musculoskeletal overload [34]. Furthermore, while spending much time using laptops and smartphones to study and support leisure activities, they tend to adopt incorrect postures, leading to musculoskeletal alteration and pain, especially to the neck and the spine [35]. Haroon et al. [36] reported a high incidence of MP in Karachi's university medical students, identifying the usage of laptops for more than three hours per day as a risk factor for neck pain. An online survey [37] conducted among students from eight universities of Hong Kong highlighted that over 90% of the 387 participants suffered pain in the previous six months; listing shoulder (58.5%), head (56.3%), and lower back (41.2%) as the most common affected sites. Vujcic et al. [38] found a high prevalence of low back pain affecting daily activities, especially in females, among Belgrade's university medical students. Kędra et al. [39] found some differences in the manifestation of low back pain between high- and medium-level physically active and physically inactive students attending physical education courses. They reported that inactive students more commonly referred mild to moderate pain; conversely, severe pain was prevalently accused by physically active students. The authors noted that trained students had a higher frequency of low back pain manifestation than untrained students; however, low back pain occurred more frequently in physically inactive students while doing simple activities like sitting, standing, and doing housework.

This study aimed to survey the PA levels and their correlation to MP among university students from Italy, before and during the pandemic restriction, therefore analyzing the impact of COVID-19 restrictions on pain and fatigue affecting daily life activities.

2. Materials and Methods

2.1. Design

This study employs an online survey addressed to Italian universities students through Google Forms web survey platform (Google LLC, Mountain View, CA, United States). The online survey was sent through social media such as Instagram and Facebook, sent to personal contacts and university students via WhatsApp and email. Participants were informed about the aims of the study, data anonymization, and protection, and were asked to provide informed consent before participation: "The data of this survey are anonymous, and their confidentiality will be guaranteed in compliance with the Italian and European legislation on the protection of personal data. We remind you that participation is voluntary, and therefore you can withdraw or give up at any time. The participant, adequately informed of the methods and purposes of the research described above, gives his consent to his participation, ensuring that his personal data will be treated anonymously.". The Local Ethics Committee approved the study of the Research Center on Motor Activities (CRAM), University of Catania (Protocol Number: CRAM-011-2020-16 / 03/2020), in accordance with the Declaration of Helsinki.

2.2. Participants

A total of 2044 Italian university students completed the online Google form questionnaire during six weeks (from February 8 to March 21, 2021) during the COVID-19 lockdown in Italy. To minimize the incidence of incorrect, duplicate, and inconsistent responses, a data cleansing process has been applied to remove ineligible data following the guidelines of the American Association for Public Opinion Research [40]. The eligible responses for this study were 1654, 1026 from females (62%), and 628 from males (38%).

2.3. *Questionnaire*

The online questionnaire (https://forms.gle/dzCy8MSdYUdq3wEb8) aimed to investigate the effect of a sedentary lifestyle and the presence of spine pain eventually due to the pandemic restriction among university students. The questionnaire was divided into four sections. The first (1) section comprised demographic, anthropometric, socioeconomic data, health status, and lifestyle questions. In addition, it introduces questions concerning PA levels before and during the COVID-19 pandemic, whether weight gain had occurred during one year of restrictions, and how many hours were spent during the day due to online distance learning. The second (2) and third (3) sections comprised cervical and lumbar questions investigating whether the students ever experienced spine pain before the pandemic or if the pain occurred for the first time during the pandemic, pain score based on Verbal Descriptive Scale (VDS) [41], pain frequency during the week/month. Furthermore, in which moment of the day and posture the pain occurs, symptoms related to the pain, and if they use drugs or some specific exercise to reduce the pain. The fourth (4) section was an adapted version of the SF-36 "limitation of activities" part [42] which investigated the perception of breathlessness, i.e., air hunger, tachycardia, perceived during the COVID-19 emergency (from March 2020 to March 2021) due to anti-infection masks usage. This section comprised five questions with three possible answers, each of them related to a specific score: no reduction = 2, mild reduction = 1, severe reduction = 0. Based on the SF-36 recommendations for scoring protocol, participants of the study achieving a high overall score were classified as no fatigue subjects; meanwhile, those with a low overall score were classified as moderate fatigue subjects, according to the SF-36 classification method.

2.4. *Statistical analysis*

Statistical analysis was performed using R Project for Statistical Computing (Vienna, Austria) [43,44] and Jamovi (Version 1.6, Sydney, Australia) [45]. The analysis was made with the use of descriptive statistics. Statistical differences between groups were tested using the t-test, Chi-square test, Kendall-tau rank correlation coefficient. The odds ratio

(OR) and corresponding 95% confidence interval (CI) were calculated. Levels of significance were set at $\alpha < 0.05$.

3. Results

3.1. General characteristics of the study population

Baseline characteristics of the study subjects are displayed in Table 1. Overall, the study sample (n = 1654) comprised 62% females and 38% males. The sample consists of university students whose mean age was 22.51 ± 3.12 (p-value < 0.05), height 169.04 ± 8.84 centimetres, weight 65.24 ± 13.38 kg, and body mass index (BMI) was 22.7 ± 3.5 kg/m^2. The values of BMI identified three categories: underweight (BMI < 18.5), normal weight (BMI 18.5–24.9), and overweight (BMI > 25.0), 71.1% of participants were classified as normal-weight subjects.

Table 1. Characteristics of participants

	(n)	(%)
Participants	1654	
Female	1026	62
Male	628	38
Underweight (BMI)	130	7.9
Normal weight (BMI)	1176	71.1
Overweight (BMI)	348	21

n: number; %: percentage, BMI: Body mass index.

3.2. Physical activity levels before and after one year of COVID-19 pandemic in Italy

Participants gave information about PA levels before the pandemic, i.e., before March 2020, and during the pandemic, i.e., from March 2020 to March 2021, considering whether the pandemic had increased or decreased PA. The subjects were therefore clustered into four categories depending on their level of PA per week: no activity (0 mins/week), light activity (<140 mins/week of PA), moderate activity (≃ 150 mins/week of PA), high activity (> 200 mins/week of PA). Before the pandemic, the total number of participants is distributed according to activity levels: 19.9% no activity, 30,1% light activity, 21.5% moderate activity, and 28,5% high activity. During one year of pandemic restriction, the total number of participants is distributed according to activity levels:

30.6% no activity, 48.1% light activity, 10.9% moderate activity, and 10.5% high activity, Table 2. The data reports an increase in no activity behavior and a drastic decrease of moderate and high PA levels following one year of pandemic. However, the percentage of those practicing light levels of PA recorded an increase of 18%.

Table 2. Physical activity levels before and during the pandemic

	Before the pandemic		During the pandemic		
	(n)	(%)	(n)	(%)	p-value*
Absent	328	19.9	506	30.6	<0.001
Light	498	30.1	796	48.1	
Moderate	356	21.5	180	10.9	
High	472	28.5	172	10.5	

n: number; %: percentage, *according to chi-square test.

The fourth section measured the fatigue levels, specifically by investigating the perception of breathlessness, i.e., air hunger, tachycardia, perceived during the pandemic. The mean average score was 6.37 ± 2.89, attesting to an overall high score for this section. The density plot, Figure 1(a), presents a left asymmetrical skewness of the data (skewness = -0.48). Additionally, the boxplot, Figure 1(b), shows the left whisker longer than the right one, meaning that the distribution tail is longer at left, namely, the students' fatigue levels distribution is clustered to a high score; therefore, the students did not experience high levels of fatigue due to anti-infection mask usage during COVID-19.

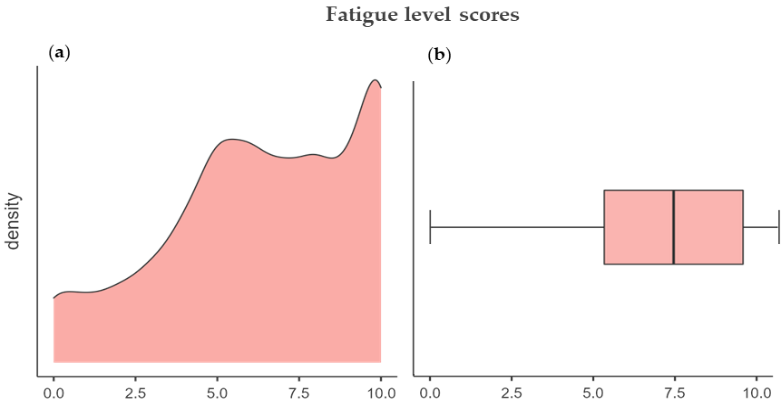

Figure 1. (a) density plot showing the major concentration of scores. (b) boxplot showing the difference of distribution.

Secondly, students have been divided into two groups, PA < 150 mins/week and PA ≥ 150 mins/week, and then crossed by the presence of neck pain, low back pain, or both pains. As reported in Table 3, 50.5% of them stated to experience pain, and those with neck and low back pain belong predominantly to the group of individuals practicing PA < 150 mins/week. Data suggest that students are more prone to suffer neck pain than low back pain, 43.5% and 33.5%, respectively. Neck pain is the most frequently reported site of pain for both PA < 150 mins/week and PA ≥ 150 mins/week groups.

Table 3. Students with musculoskeletal pain divided by physical activity levels

	Total		Neck pain		Only neck pain		Both pains		Low back pain		Only low back pain		
	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	p-value*
PA < 150	680	41.7	590	35.7	216	13.1	292	17.6	470	28.4	172	10.4	0.0184
PA ≥ 150	146	8.8	128	7.8	66	4	50	3	84	5	30	1.8	

PA<150: physical activity lesser than 150 mins/week, PA ≥ 150: physical activity at least 150 mins/week, n: number; %: percentage based on the whole population, ∗according to chi-square test.

3.3. Body weight and seated time due to activities restriction during one year of COVID-19 pandemic in Italy

A total of 861 students (52.1%) reported an increase in body weight after one year. Specifically, 61.9% reported a body weight increase of less than 5 kg, 35.1% a body weight increase ranged between 5 kg and 10 kg, and only 3% stated a body weight increase over 10 kg.

Almost all the students stated a seated time higher than 4 hours/day. The 46.9% reported a seated time ranged between 4 and 8 hours, 37.1% between 8 and 12 hours, and a small percentage, 8.2%, higher than 12 hours.

Among those participants who reported PA levels lower than 150 mins/week together with a seated time > 8 hours/day (38.8% of total) Figure 2, 40.8% did not report a body weight increase, 34.6% stated a body weight increase lesser than 5 kg, 21.5% a body weight increase ranged between 5 kg and 10 kg, 3.1% stated a body weight increase over 10 kg. This data suggests a strong correlation between a moderate-to-high body weight increase and PA levels lower than 150 mins/week. The odds of weight increase for those showing a sedentary behavior are 5.36 (OR with 95% CI ranging from 3.04 to 9.47) times of those practicing PA, Table A1.

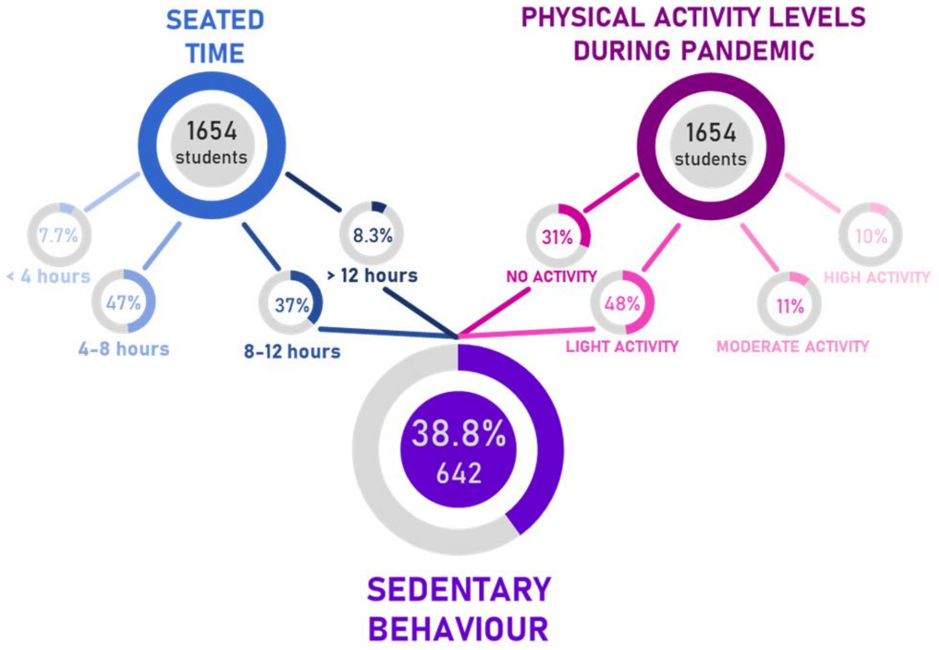

Figure 2. Estimation of sedentary participants depending on seated time and physical activity levels during pandemic.

3.4. Neck pain during one year of COVID-19 pandemic in Italy

Participants were asked to give information about neck pain onset during the pandemic period or if they were used to experience neck pain even before the pandemic. 718/1654 students (43.5%) reported the presence of neck pain, Table 4. Concerning the neck pain group, 55.7% declared having experienced neck pain within the last 4 months, 16.4% within the last 9 months, and 27.9% for more than 12 months. The pain frequency declared by the students classifies them into different categories; those with recurrent neck pain, 18.4%, stated to experience it up to 16 times/month, while 26.7% experience it up to 8 times/month. The rest of the students reports a low frequency of pain, precisely 26.2% stated to experience neck pain up to 4 times/month, while the remaining 28.7% experience it up to 2 times/month. The VDS score of those experiencing neck pain is mild for 32.3%, moderate for 45.7%, severe for 18.4%, very severe for 3.6%, and no students reported worst possible pain. The participants were asked to indicate the specific time window of the day when the pain occurs. Most of them experience neck pain after several hours of study, 73.3%, a minor percentage reports experiencing neck pain in the morning after waking up, 11.7%, 9.2% experience neck pain in the late evening and, a small percentage, 5.8%, do not find a specific time window when the pain occurs. The posture in which the pain occurs was a valuable condition to analyze. The majority of participants, 60.7%, stated that the pain arises when seated, while the 30.4% cannot evaluate a specific circumstance. The remaining percentage, 8.9%, experience pain when walking, doing PA, or doing housework. Secondly, all participants were asked about the strategies to relieve pain. 35.4% stated to prefer keeping the pain during daily activities until it resolves independently, while 32.9% prefer to perform a specific exercise to relieve the pain. 18.1% choose a pharmacological method, and the remaining percentage of students, 13.6%, prefer to sleep until the pain resolves by itself. Among those who reported performing specific exercises, the neck muscle stretching and joint mobilization exercises are the most common strategies performed, 77.1%, while 16.1% prefer counter-resistance isometric exercises for the neck muscle. The remaining 6.8% find relief by performing sports activities, Table 5. Lastly, all participants were asked to recognize whether the pandemic restrictions had affected the pain onset or not. Most of the students with neck pain, 47.6%, stated that the restriction caused a slight pain increase, while 13.4% stated a severe pain increase. A moderate percentage of them, 17%, experienced neck pain for the first time due to the pandemic restriction, while the rest of those with neck pain, 21.2%, do not impute the neck pain onset to pandemic restriction.

Table 4. Overall characteristics of musculoskeletal pains

	Neck pain students (718)		Low back pain students (554)	
	(n)	(%)	(n)	(%)
Temporal window				
Pain within the last 4 months	400	55.7	260	46.9
Pain within the last 9 months	118	16.4	144	26.0
Pain more than 12 months	200	27.9	150	27.1
Frequency				
16 times/month	132	18.4	130	23.5
8 times/month	192	26.7	166	30.0
4 times/month	188	26.2	124	22.3
2 times/month	206	28.7	134	24.2
Pain intensity (VDS scale)				
0 – no pain	0	0	0	0
1 – mild pain	232	32.3	196	35.4
2 – moderate pain	328	45.7	218	39.4
3 – severe pain	132	18.4	110	19.9
4 – very severe pain	26	3.6	30	5.4
5 – worst pain ever	0	0	0	0
Daytime window				
After several hours of study	526	73.3	386	69.7
After waking up in the morning	84	11.7	54	9.7
In the late evening	66	9.2	62	11.2
No specific moment	42	5.8	52	9.4
Pain posture onset				
Sitting	436	60.7	280	50.5
Walking/housework	64	8.9	166	30.0
No specific circumstance	218	30.4	108	19.5
Pain relief strategy				
Performing exercises	236	32.9	210	37.9
Medicines	130	18.1	46	8.3
Sleep	98	13.6	88	15.9
Wait until it resolves	254	35.4	210	37.9

Table 5. Exercise classification of those choosing exercises as pain relief strategy

	Neck pain students (236)		Low back pain students (210)	
	(n)	(%)	(n)	(%)
Stretching and joint mobilization	182	77.1	186	88.6
Performing sport activities	16	6.8	8	3.8
Counter-resistance/isometric	38	16.1	16	7.6

3.5. Low back pain during one year of COVID-19 pandemic in Italy

Participants were asked to give information about low back pain onset during the pandemic period or if they experienced low back pain during the pandemic. 554/1654 students (33.5%) reported the presence of low back pain, Table 4. Concerning the students reporting low back pain, 46.9% stated to experience it within the last 4 months, 26% within the last 9 months, and 27.1% for more than 12 months. The percentage of students with low back pain who experienced the pain up to 16 times/month is 23.5%, while 30% stated to experience it up to 8 times/month. The 22.3% reports a mild frequency of 4 times/month, and a relatively low frequency, 2 times/month, is reported by 24.2%. The VDS score from those experiencing low back pain is mild pain for 35.4%, moderate pain for 39.4%, severe pain for 19.9%, very severe pain for 5.4%, no students reported worst possible pain. The participants were asked to indicate the specific time window of the day when the pain occurs. A high prevalence, 69.7%, of reports referred pain onset after several hours of study, 11.2% stated to experience pain when resting in the late evening, 9.7% identify the moment after waking up, in the morning, as the pain apex, and lastly, a 9.4% do not find a specific time window when the pain occurs. The posture where the pain occurs was a valuable condition to analyze. Half of the low back pain students group, 50.5%, stated that the pain arises when seated, 19.5% cannot evaluate a specific circumstance, while 30% experience the pain when walking, doing PA, or doing housework. All participants were asked about the strategies to relieve pain. 37.9% stated to prefer keeping the pain during daily activities until it resolves independently, another 37.9% prefer to perform a specific exercise to relieve the pain, 15.9% of them prefer to sleep until the pain resolves, and only 8.3% resort to the pharmacological method to relieve pain. Those performing specific exercises stated to prefer muscle stretching and joint mobilization exercises for the back, representing 88.6%, while 7.6% perform isometric exercises, e.g., core-stability, and the remaining 3.8% resort to sports activities, e.g., swimming or running, Table 5. Lastly, all participants were asked to recognize whether the pandemic restrictions had affected the pain onset or not. A slight pain increase among the students with low back pain due to pandemic restriction is stated by

47.3%, while 22.4% stated a severe pain increase. The 13% of them experienced low back pain during the pandemic for the first time, while the rest of those with low back pain, 15.5%, do not impute the pain onset to pandemic restriction.

3.6. Neck and low back pain and sedentary behavior during one year of COVID-19 pandemic in Italy

An in-depth data analysis was performed by crossing neck pain and low back pain with sedentary conditions. Sedentary behavior (SB) was referred to individuals with PA levels < 150 mins/week (78.6% of the total of the students) and who also seated more than 8 hours/day (45.3% of total the students). Sedentary students result as 38.8% of the total (642/1654). A percentage of 52.3% and 38.9% of sedentary students stated to experience neck pain and low back pain. These results might suggest that 1 out of 2 students and 1 out of 3 students having SB can be prone to suffer from neck pain and low back pain, respectively. The OR for the neck pain sample is 1.95 with a 95% CI ranging from 1.44 to 2.64, Table A2. The OR for the low back pain sample is 1.79 with a 95% CI ranging from 1.29 to 2.49, Table A3.

3.7. Neck VDS scores and pain frequency compared to physical activity levels

Data of neck VDS score and pain frequency have been crossed with PA levels to understand if PA can modulate pain perception and occurrence. VDS contingency table, Table 6, shows the highest number of students experiencing pain concentrated between No PA and Light PA with Mild Pain and Moderate Pain. The reported percentages show that the highest concentration is in those practicing Light PA and experiencing Moderate Pain, 24.2% of the total. The Chi-square test p-value < 0.05 for the VDS neck score attests that the variables are dependent; the Kendall-tau value shows a mild negative association between PA and pain perception levels.

Pain frequency contingency table, Table 7, shows the frequency of neck pain during the month almost equally shared among all the groups, except for the 16 times/month group, which shows to comprise the lowest number of individuals. The reported percentages show that the highest concentration is in those practicing Light PA and experiencing the pain two times/month, 16.7% of the total. The Chi-square test p-value < 0.05 for the neck pain frequency attests that the variables are dependent; the Kendall-tau value shows a mild positive association between PA and pain frequency levels.

Table 6. Contingency table of physical activity levels and VDS neck scores

	VDS levels										
	Mild pain		Moderate pain		Severe pain		Very severe pain		Total	χ^{2*}	τb**
	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)/(%)		
No PA	82	11.4	86	12	52	7.2	8	1.1	228 / 31.8	0.020	-0.002
Light PA	110	15.3	174	24.2	62	8.6	16	2.2	362 / 50.4		
Moderate PA	22	3.1	33	4.6	5	0.7	6	0.8	66 / 9.2		
High PA	18	2.5	32	4.5	12	1.7	0	0	62 / 8.6		
Total	232	32.3	325	45.3	131	18.2	30	4.2	718 / 100		

n: number; %: percentage, No PA: no physical activity, Light PA: <150 mins/week of MVPA, Moderate PA: ≃ 150 mins/week of MVPA, High PA: > 200 mins/week of MVPA, VDS: verbal descriptive scale, *Chi-square p-value, **Kendall-tau value.

Table 7. Contingency table of physical activity levels and neck pain frequency

	Monthly frequencies										
	2 times/month		4 times/month		8 times/month		16 times/month		Total	χ^{2*}	τb**
	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)/(%)		
No PA	62	8.6	62	8.6	60	8.4	44	6.1	228 / 31.8	0.010	0.02
Light PA	120	16.7	82	11.4	98	13.6	62	8.6	362 / 50.4		
Moderate PA	18	2.5	24	3.3	16	2.2	8	1.1	66 / 9.2		
High PA	6	0.8	20	2.8	18	2.5	18	2.5	62 / 8.6		
Total	206	28.7	188	26.2	192	26.7	132	18.4	718 / 100		

n: number; %: percentage, No PA: no physical activity, Light PA: <150 mins/week of MVPA, Moderate PA: ≃ 150 mins/week of MVPA, High PA: > 200 mins/week of MVPA, *Chi-square p-value, **Kendall-tau value.

The stacked bar of neck pain shows the correlation between PA levels, VDS score, Figure 3(a), and pain frequency, Figure 3(b). Students belonging to No PA and Light PA categories represent most subjects with pain, suggesting that those practicing PA < 150 mins/week (No PA and Light PA subjects) are more prone to experience pain. Secondly, those with a VDS score = Severe pain or Very severe pain are expressed as a higher percentage in groups No PA and Light PA. Among subjects with PA ≥ 150 mins/week (Moderate and High PA), the higher percentages of VDS score are represented by mild and moderate VDS levels of pain. This result suggests a lower existence of students with pain and, in addition, lower pain perception among those who comply with WHO guidelines. Similarly, the pain frequency stacked bar, Figure 3(b), shows an analogous trend. Nevertheless, a notable percentage of those experiencing pain 16 times/month in the High PA group suggest a possible relationship between pain frequency and high activity levels. Noteworthy, the population suffering from neck pain is more concentrated in Light PA group for both plots.

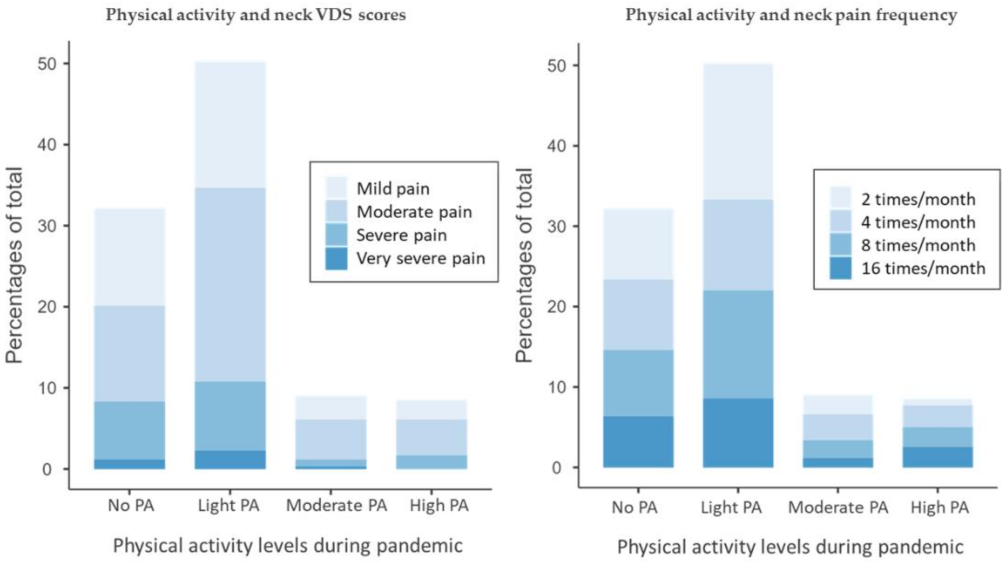

Figure 3. (a) stacked bar of VDS neck score and physical activity levels. (b) stacked bar of pain frequency and physical activity levels. No Pa: no physical activity, Light PA: physical activity < 140 mins/week, Moderate PA: ≃ 150 mins/week, High PA: > 200 mins/week.

3.8. Low back VDS scores and pain frequency compared to physical activity levels

Data of low back VDS score and pain frequency have been crossed with PA levels to understand if PA can modulate pain perception and occurrence. VDS contingency table, Table 8, shows the highest number of students experiencing pain concentrated between No PA and Light PA with Mild Pain and Moderate Pain. The highest concentration is in those practicing Light PA and experiencing Mild Pain, 21.3% of the total. The Chi-square test p-value < 0.05 for the VDS low back score attests that the variables are dependent; the Kendall-tau value shows a mild negative association between PA and pain perception levels.

Pain frequency contingency table, Table 9, shows that the frequency of low back pain during the month is almost equally shared among all the groups, slightly higher for the 8 times/month group. The reported percentages show that the highest concentration is in those practicing Light PA and experiencing pain 8 times/month, 16.6% of the total. The Chi-square test p-value < 0.05 for the low back pain frequency attests that the variables are dependent; the Kendall-tau value shows a mild negative association between PA and pain frequency levels.

Table 8. Contingency table of physical activity levels and VDS low back scores

	VDS levels										
	Mild pain		Moderate pain		Severe pain		Very severe pain		Total	χ^{2*}	τb**
	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)/(%)		
No PA	46	8.3	80	14.4	42	7.6	12	2.2	180 / 32.5		
Light PA	118	21.3	110	19.9	48	8.7	14	2.5	290 / 52.3		
Moderate PA	18	3.2	18	3.2	12	2.2	0	0	48 / 8.7	0.026	-0.09
High PA	14	2.5	10	1.8	8	1.4	4	0.7	36 / 6.5		
Total	196	35.4	218	39.4	110	19.9	30	5.4	554		

n: number; %: percentage, No PA: no physical activity, Light PA: <150 mins/week of MVPA, Moderate PA: ≃ 150 mins/week of MVPA, High PA: > 200 mins/week of MVPA, VDS: verbal descriptive scale, *Chi-square p-value, **Kendall-tau value.

Table 9. Contingency table of physical activity levels and low back pain frequency

	Monthly frequencies										
	2 times/month		4 times/month		8 times/month		16 times/month		Total	χ^{2*}	τb**
	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)	(n)/(%)		
No PA	42	7.6	36	6.5	48	8.7	54	9.7	180 / 32.5		
Light PA	66	11.9	74	13.4	92	16.6	58	10.5	290 / 52.3		
Moderate PA	18	3.2	8	1.4	16	2.9	6	1.1	48 / 8.7	0.037	-0.05
High PA	8	1.4	6	1.1	9	1.6	13	2.3	36 / 6.5		
Total	134	24.2	124	22.4	165	29.8	131	23.6	554		

n: number; %: percentage, No PA: no physical activity, Light PA: <150 mins/week of MVPA, Moderate PA: ≃ 150 mins/week of MVPA, High PA: > 200 mins/week of MVPA, *Chi-square p-value, **Kendall-tau value.

The stacked bar of low back pain shows the correlation between PA levels, VDS score, Figure 4(a), and pain frequency, Figure 4(b). Its trend is in accordance with the neck pain stacked bar. Students belonging to No PA and Light PA categories represent most subjects with pain, suggesting that those with PA < 150 mins/week are more prone to experience pain. Secondly, those with a VDS score resulting from severe pain or very severe pain are mainly present in No PA and Light PA groups. The group Moderate PA shows a similar trend for all pain levels, although very severe pain is not present. This data might suggest that PA level close to 150 mins/week, i.e., Moderate PA, is associated with lower pain perception, while PA levels lower or higher than WHO guidelines might determine an increase in pain perception. Similarly, the pain frequency stacked bar, Figure 4(b), shows an analogous trend. Nevertheless, there is a notable percentage of those experiencing pain 16 times/month and 8 times/month in the No PA and Light PA groups, suggesting a possible relationship between pain frequency and low activity levels. A considerable percentage of those with 16 times/month pain presence is also represented in the High PA group. This trend is similar to the VDS stacked bar and might suggest that PA levels close to 150 mins/week, Moderate PA, are associated with a lower pain frequency, while PA levels lower or higher than WHO guidelines might determine an increase in pain frequency. Noteworthy, the population suffering from low back pain is more concentrated in Light PA group for both plots.

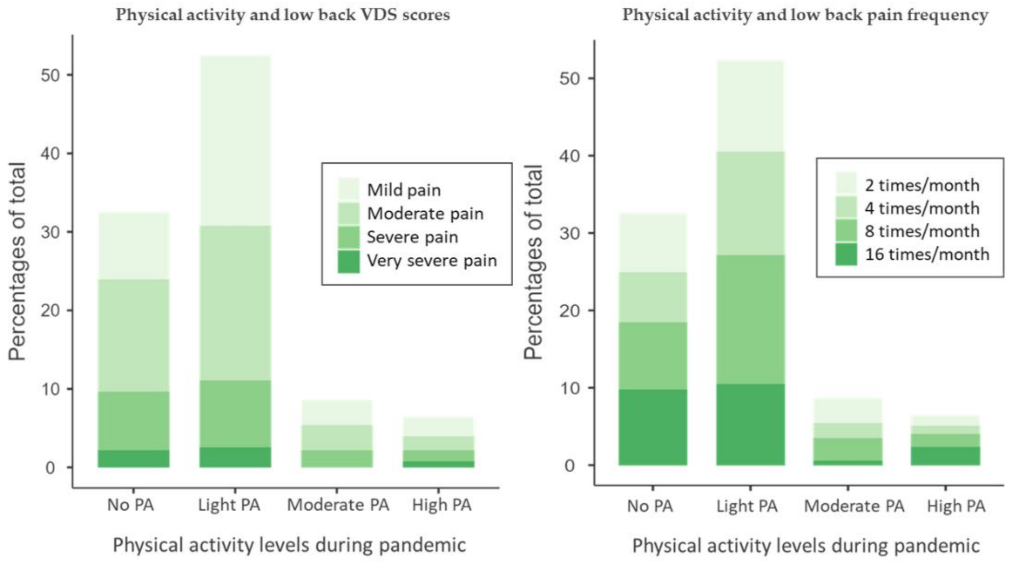

Figure 4. (a) stacked bar of VDS low back score and physical activity levels. (b) stacked bar of pain frequency and physical activity levels. No Pa: no physical activity, Light PA: physical activity < 140 mins/week, Moderate PA: ≃ 150 mins/week, High PA: > 200 mins/week.

4. Discussion

The quarantine due to COVID-19 imposed a severe daily activities reduction and inevitably increased the onset of MP. In the available literature concerning the COVID-19 aspects, the relationship between PA reduction and MP has not yet been investigated. During the last year, several studies assessed a reduction in PA levels in the general population following pandemic restriction, while other studies evaluated MP among students in the previous years. This is the first study, to the best of our knowledge, discussing the relationship between the reduction of PA levels, the SB increase, and the MP onset in university students after one year of COVID-19 restrictions in Italy.

The disease outbreak has changed young people's lives who were used to spending most of the day away from home between study, work, commitments, friends, sports, and entertainment. Figure 5 shows the primary outcomes of this study.

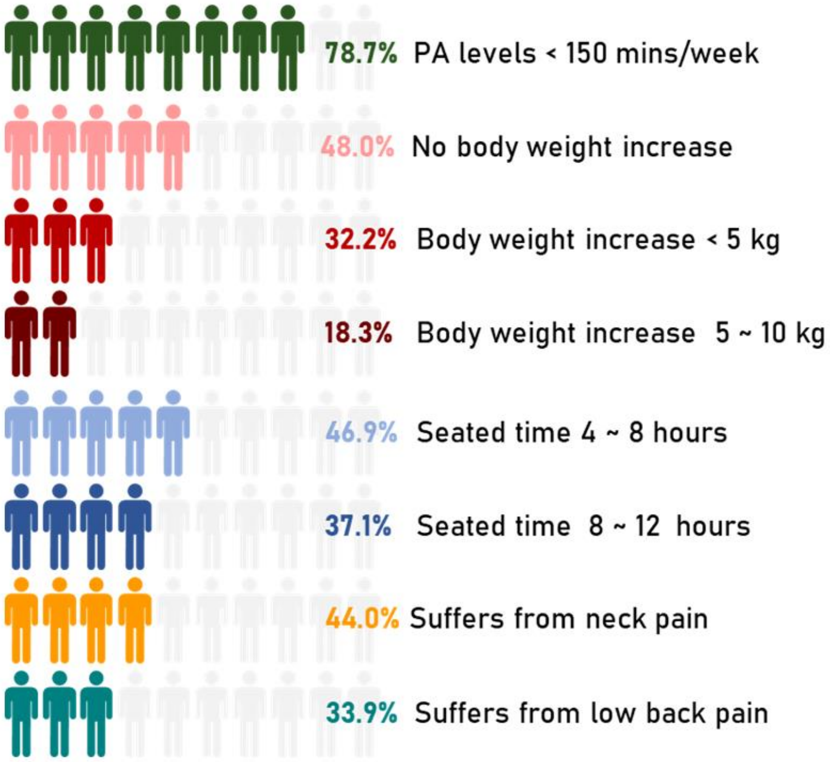

Figure 5. primary outcomes of the present study. The representation is counted as n/10 based on the respective data.

During the first period of the pandemic, March-May 2020, sport-related public facilities were closed, making difficult to practice jogging, running, or walking long distances. Maugeri et al. [46] conducted an epidemiological analysis during the first quarantine period on 2524 Italian subjects aged 18 and 70. PA levels suffered a moderate decrease, those who practiced moderate activity decreased by about 6%, while those who practiced intense activity by 11%. Some sports activities resumed from June but starting from October, with the increase in the number of infections, sports centers closed once more, and the red zones blocked the students at home again. This event did not permit the expected recovery of sports activities, so according to our data, about 30% of the participants did not return to the PA levels they had before the pandemic after one year of pandemic. Figure 6 shows how PA levels have changed between before and during the pandemic in one year. About 60% of those who were inactive before the pandemic did not change this behavior during the pandemic, while 35% practicing light activity before the pandemic became inactive during the pandemic. Interestingly, the highest percentage of people for each group, except for the inactive ones, is channeled into the group of individuals performing light activity during the pandemic. This may have been caused by the severe restrictions, although those who played sports before the pandemic tried to maintain an adequate lifestyle. The increase in the number of subjects performing light levels PA is due to the presence of those who started practicing PA (14.1%), probably to overcome the severe limitations of daily activities, and those who reduced their PA levels from moderate/high to light (27.1% and 23.1%, respectively). Among those who did not practice PA before the pandemic (19.9%), 40.2% started practicing PA during the pandemic. These findings contrast with Hall et al. [47], where they speculated that those already sedentary before the pandemic would hardly increase their PA levels during the pandemic. Several studies analyzed reduced PA and SB worldwide [48-51]. Many authors decreed a possible end of these conditions in the summer of 2020, although unfortunately, starting from October 2020, the severe limitations were back in effect in Italy. It was predictable that the lockdown would have resulted in inactivity and SB; however, no preventive measures, such as promoting home-based sports activities, were taken to avoid this trend [52]. All the data from the authors above corroborate the findings of this study that people have changed their lifestyle by reducing PA levels and increasing sitting time even if, as it was stated previously, a small percentage started to practice PA during the pandemic restriction, probably thanks to more time available. WHO guidelines of PA and SB [53] recommend doing at least 150 min of moderate-intensity PA throughout the week and limiting sedentary time. In line with these guidelines, the students who reported MP were divided into two groups based on the PA levels adherence. The data show a high prevalence of students reporting pain in the PA < 150 mins/week group, representing 41.7% versus 8.8% of those performing PA ≥ 150 mins/week.

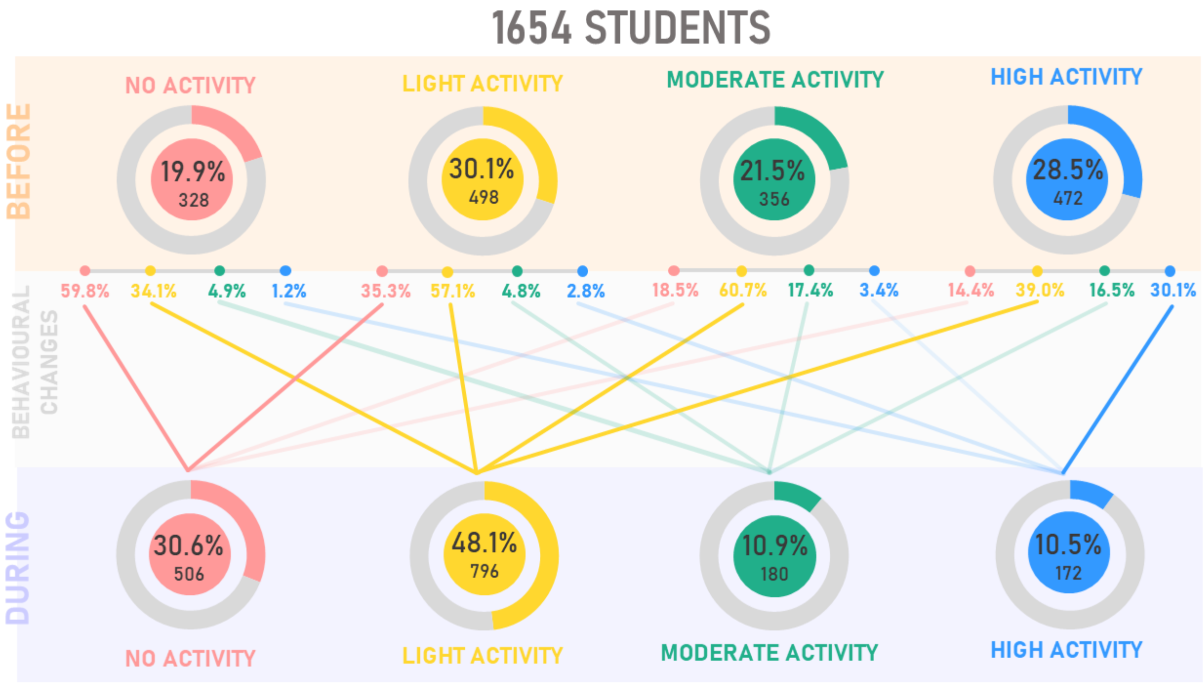

Figure 6. Physical activity changes before (March 2020) and during (March 2020/2021) one year of pandemic restrictions.

Concerning the neck pain, 43.5% of the whole sample assessed to experience neck pain, and among them, 72.2% stated the neck pain onset during the months of the pandemic. The 73.3% of the students who experienced pain also suffered from it after several hours of study, as expected since they had to attend courses through electronic devices due to the restriction measures. As reported by Mowatt et al. [54], the most frequent health problems among those using electronic devices for several hours are computer vision syndrome (CVS), neck, shoulder, and back pain, and specifically, 89.9%

of undergraduate university students have a prevalence of these health problems [55]. Prolonged use of mobile phones, tablets, or laptops to attend online lessons or just to spend time on social media may negatively affect neck and shoulders pain [56]. This relationship, anyhow, has been validated by several epidemiological studies, which confirmed that assuming a wrong posture for many hours and having a SB is strongly related to the severity of neck pain [57-61]. In line with these considerations, our data shows how the levels of VDS score and frequency of neck pain onset are considerably lower for students performing moderate to high PA levels compared to those with light or no PA levels. These findings confirm the hypothesis of a greater likelihood of having neck pain for those with low levels of PA stated by Scarabottolo et al. [62] and are in line with Guddal et al. [63], who observed a positive association between neck pain and PA levels. Conversely, we strongly disagree with Sitthipornvorakul et al. [64], who assert strong evidence for no association between PA and neck pain.

While Haroon et al. [36] stated the low back as the region with the highest frequency of pain, our sample reported the neck as the highest region of pain. Our results align with another study [65] conducted among Italian students, which stated a high incidence of low back pain. Students with low back pain represent 33.5% of the whole sample, and of those, 72.9% stated the low back pain onset during the COVID-19 months. 69.7% experienced the pain after several hours of study, probably related to a wrong posture assumed during it, as for the neck pain. Stressors, fear of pain, and lack of PA, according to Amelot et al. [66], are the most critical factors affecting LBP occurrence. In the present study, only PA levels have been evaluated, but in line with another analysis conducted among the Italian population [67], psychosocial repercussions over mental health were present. As for neck pain, VDS score and frequency for low back pain are considerably lower for students with moderate to high PA levels compared to those with light or no PA. These results are in line with the findings of Wedderkopp et al. [68], where physically active students had a low predisposition to experience back pain. Likewise, Guddal et al. [63] observed that moderate levels of PA were correlated to reduced LBP onset. However, as we highlighted in the results section, excessively high PA levels might increase the risk of spinal pain because intense activities might contribute to a wrong posture and lead to pain onset [69].

Differently from our results, two studies [70,71], pointed the absence of correlation between a sedentary lifestyle and the occurrence of MP in medical students with LBP. Our data contrast these authors' point of view because the OR between SB and low back pain was 1.79 (95% CI, 1.29 - 2.49), Table A2, so a correlation between SB and low back pain onset is present. However, these authors did not clearly state what describes SB. While Moroder [70] did not classify sitting time and PA levels threshold as sedentary, Chen S.M. [71] considered only time spent sitting, omitting the PA levels. Regarding our data, the Kendall-tau value shows a positive correlation, meaning that the LBP onset might occur when SB increases. Even if this topic is still debated among the scientific community, our findings strongly agree with a recent meta-analysis published in Nature journal by Alzahrani et al. [72], who speculated over the importance of medium to moderate PA levels to decrease the risk of LBP. Epidemiological researches have shown that assuming a wrong posture for a prolonged time, sitting for many hours, or just showing an SB are strong predictors of adverse health outcomes such as cardiovascular diseases [73], diabetes [74], cancer [75], musculoskeletal pain [76], depression [77]. The present study aimed to investigate only the correlation between SB and MP onset. The students showing an SB were 38.8% of the total and, concerning this group, 52.3% and 38.9% stated to suffer from neck and low back pain, respectively. These percentages are considerably high because it predisposes 1 out of 2 students to start experiencing pain at an even younger age. In line with this assumption, Shrier and Feldman [78,79] identified the prolonged sitting position as a prevalent risk factor for MP onset. In general, it can be assumed that the more frequent students are physically inactive during the week, the more frequent is the risk of suffering from chronic pain [80].

Concerning the pain relief strategies, Mimi Mun Yee Tse et al. [81] , by accomplishing a similar study all over university students in Hong Kong, stated a high percentage of them adopting pharmacological methods to contrast MP. This condition differs from our data because our sample's most pain relief strategy is to perform physical exercises or prefer to wait until the pain resolves. One out of three students favors exercising to reduce the pain; the rest of them are used to take medication, sleep, or rest. It may predispose them to be more prone to chronic and prolonged pain problems lifelong. Those experiencing pain should prefer non-pharmacological treatment initially, including exercises or rehabilitation protocols [82]. Therefore, education for young is needed to give them resources to manage their condition, such as exercises sheets, pain management guidelines, or prevention methods [83,84].

In a commentary of Hall et al. [47], the authors wondered if COVID-19 is making the world move even less than before. After one year of pandemic, our data attempted to find an answer. PA levels were drastically reduced, and, concerning the authors' worries about the possibility of SB as a new societal norm, our findings may suggest that this trend is being observed. Our data indicate that PA and sedentary lifestyle changes during the pandemic negatively affected MP, although other factors (psychosocial, diet, smoke), which were not investigated herein, could concur with this scenario. Trivial as it may seem, yet simply carrying out a student's daily activities such as leaving home in the morning, going to university, walking with friends, visiting a shop can be worth maintaining the body active and thus avoiding the onset of pain [85].

Further studies are needed to understand the aspects related to sedentary lifestyle and pain. What is clear is that we have to work on two fronts since, following this trend, the 2025 global PA target (10% reduction of physical inactivity) will not be met [86]. Firstly, National governments should develop new approaches to engage the unwilling population to increase or start PA programs, especially after one year of restrictions due to the pandemic, which can induce MPs. Secondly, there is to understand the reasons behind some students' indifference towards PA since, during the pandemic, they could have trained at home to counterbalance psychological and physiological distress [87,88]. Nevertheless, these data suggest that many students remained inactive. The last decade's general increase of physical inactivity prompted the WHO in 2018 to provide a plan until 2030 to encourage the world population to be more active [89]. The aim was to invest in policies to promote sports activities, jogging, or just recreational activities to contribute to achieving different sustainable development goals by 2030. Concluding, in line with WHO guidelines, we suggest the need to plan educational programs to encourage students to exercise practice. For instance, with the help of professionals, e.g. kinesiologists, universities could plan a 10-minutes break within the lessons aimed at performing simple exercises to keep the body active and avoid the classic pains of incorrect posture. Next to coffee and snack machines, aerobic devices, e.g., treadmill or cyclette, could be positioned to motivate students to practice more PA even when they are at university.

This study has some limitations that need to be considered in the results' interpretation. First, the questionnaire was administered through online channels, which may determine a disinterest in answering all questions carefully. Second, it was a self-reported questionnaire, which can indicate an underestimation or overestimation of the self-conditions based on the questions. Third, a bias regarding PA levels before the pandemic may be present due to the time elapsed. Fourth, this study has a cross-sectional design, so inference must be evaluated carefully. Conversely, a large number of responses, the presence of different check-questions useful to reduce the bias, the strong consistency thanks to a close age range, and the reduced likelihood of having other conditions that could lead to MP, enhance the study's strength.

In terms of future research, we expect to conduct research similar to this after we recover entirely from the COVID-19 pandemic to determine if PA and SB levels retrieved after this social catastrophe and investigate more how MPs can be modulated through daily exercises.

5. Conclusions

One year of COVID-19 restrictions forced the students to reduce their daily activities and triggered, in some cases, adverse health outcomes. An overall reduction of physical activity and musculoskeletal pain onset was observed, especially for those who did not respect the WHO physical activity guidelines. These findings highlight the alarming condition of the musculoskeletal pain presence in a young population. Universities are called upon to handle this situation in the best possible way; a preventive approach is required because a young experiencing pain today could be an adult with chronic pathologies tomorrow, leading to earlier habitual use of drugs, namely, a burden for the public health.

Appendix

Table A1. Odds ratio between sedentary behavior and body weight increase

	Weight increase	No weight increase	Total	Odds ratio	τb*
Sedentary	158	484	642		
No sedentary	14	230	244	5.36 (3.04 – 9.47)	-0.213
Total	172	714	886		

Sedentary: physical activity levels < 150 mins/week and seated time > 8 hours/day, *Kendall-tau value

Table A2. Odds ratio between sedentary behavior and low back pain

	Low back pain	No low back pain	Total	Odds ratio	τb*
Sedentary	250	392	642		
No sedentary	64	180	244	1.79 (1.29 – 2.49)	0.118
Total	314	572	886		

Sedentary: physical activity levels < 150 mins/week and seated time > 8 hours/day, *Kendall-tau value

Table A3. Odds ratio between sedentary behavior and neck pain

	Neck pain	No neck pain	Total	Odds ratio	τb*
Sedentary	336	306	642		
No sedentary	88	156	244	1.95 (1.44 – 2.64)	-0.145
Total	424	462	886		

Sedentary: physical activity levels < 150 mins/week and seated time > 8 hours/day, *Kendall-tau value

Technological advancements in the analysis of human motion and posture management through digital devices

Federico Roggio [1,2] , Silvia Ravalli [1], Grazia Maugeri [1], Antonino Bianco [2], Antonio Palma [2], Michelino Di Rosa [2] and Giuseppe Musumeci [2,4,5]

[1] Department of Psychology, Educational Science and Human Movement, University of Palermo, Via Giovanni Pascoli 6, 90144 Palermo, Italy

[2] Department of Biomedical and Biotechnological Sciences, Human Anatomy and Histology Section, School of Medicine, University of Catania, Via S. Sofia 87, 95123 Catania, Italy

[3] Research Center on Motor Activities (CRAM), University of Catania, 95123 Catania, Italy;

[4] Department of Biology, College of Science and Technology, Temple University, Philadelphia, PA 19122, USA

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Introduction

Over the last decades, human movement research has made significant progress in responding to the growing medicine and sport demand for precise and accurate methods to capture human movement[90] and refine data collection[91]. Motion and posture analysis are effective tools used in diagnosis, therapy, and prevention of musculoskeletal disorders. Notably, human motion evaluation is important during functional activities in sports and rehabilitation. Nevertheless, there is a solid need to diversify the use of each system in relation to specific contexts. In some instances, 2D biomechanical analysis can offer a quick and effective method of evaluation. Movements, such as walking or running, do not require sophisticated approaches, since they are easily inspected in the sagittal plane. Otherwise, if the movement needs to be studied on multiple planes or forces investigation is required, it is more appropriate to use a 3D system, which requires in-depth expertise. Biomechanical researchers aim to standardize human movement parameters that can be understandable, comparable, and shareable with the entire scientific community. Quantitative analysis of human movements and posture is an effective tool used to evaluate the correct movement execution, identify injury risk factors[92], help clinicians make the best decision to reduce patients' recovery time, and suggest a proper treatment plan[93].

Assessing walking speed through wearable systems could be a valuable indicator of adults' health and functional status [94,95]. For example, low physical activity levels are associated with muscle weakness, decreased mobility function, and widespread pains[96]. Fast return to play sports and exercise could trigger joint pains and musculoskeletal alterations; therefore, an accurate motion and posture analysis could help planning the right approach to resume physical activity.

Hence, technological devices can broadly be used to diagnose musculoskeletal disorders and plan a preventive strategy for returning to the sport practice. Similar advice is suggested for those who return to physical activity after surgery. Long periods of inactivity caused by surgery inevitably lead to loss of muscle mass and reduction of movements fluidity; therefore, movement analysis in the return-to-daily-activities phase can be performed to detect dysfunctions and re-educate the patients.

Although marker-based and non-invasive systems are more commonly used to evaluate pathological patients, *e.g.*, subjects with spinal cord damage, amputees, strokes and cerebral palsy, scoliosis, instrumental biomechanics have the potential for reaching every subject, from the one who suffers from musculoskeletal pathologies to the one who reports only mild pain. Therefore, it is encouraged to use these devices to study every and unexplored aspect of movement science. This review aims to highlight the importance of new technologies in human movement and posture analysis, suggesting how they can strengthen orthopedics, rehabilitation, health prevention, sports science and guide the clinicians towards a personalized diagnostic process and treatment plan based on the patient’s characteristics.

From Marker-Based To Markerless Motion Analysis Systems

The optoelectronic stereophotogrammetric multi-camera capturing system is the gold standard for motion capture, tracking reflective markers placed on the body[97,98]. One of the most known, the Vicon system (Vicon Motion Systems, Oxford, UK), consists of multiple infrared cameras for kinetic, kinematic, and spatiotemporal movement analysis. The markers, positioned on anatomical landmarks in correspondence with the joints involved in the exam, allow tracking all the human motion features with high accuracy[99,100]. This system precisely evaluates each joint's movements in the space at any time, and it can define the level of functional limitation and disability resulting from the evolution of a disorder, including post-traumatic or surgical alterations. Motor control, neurosciences, cerebral palsy, lower limb amputation, and movement studies are areas whom clinical gait analysis is commonly used. The company produced a platform for the life sciences community called Nexus, a powerful, all-inclusive modeling and processing tool for movement capture. Operators can reduce the time spent processing the data by creating their workflow templates; the system automatically loads the data and produces the report in the simplest or most detailed way required. However, marker-based systems show several limitations, including long preparation times, soft tissue artifacts, or unfeasibility of specific movements due to the presence of the markers, which can hinder the correct execution of the movement[101]. These systems are pricey and require a large setting in order to place all the cameras needed for the evaluation. The markers placement on anatomical landmarks is challenging since it depends on the clinician's ability to locate them correctly and, therefore, human error could incur. Particularly for transverse plane movements, there is an inevitable variability in the marker positioning between different days or different clinicians' hands, reducing the measurements' reliability[102]. In the literature, several protocols can be found for locating joint centres or defining segment pose, as shown in Figure 1a; however, these different protocols produce variable results, especially for the sagittal plane, compared to the same gait cycles[102]. The marker application issues can limit the use of this method within certain motion analysis areas. For these reasons, nowadays, markerless systems are offering new opportunities to obtain similar results.

The markerless system presents a fast, fully automatic, and non-invasive approach to significantly improve rehabilitation and sports biomechanics research and practice. For instance, a common laboratory can investigate human motion during regular training without the long preparation times due to the markers placement and the laborious manual work. Furthermore, it can provide an effective solution for a widespread predicament in biomechanics laboratories, *i.e.*, the constant search for balance between accuracy and reproduction of motion without artifacts. Several researchers investigated the most common movements studied in biomechanics laboratories, *e.g.*, walking, jumping, and jogging, by inspecting the accuracy of markerless systems compared to marker-based techniques[103-105]. Therefore, a potential application of markerless systems in gait analysis in clinics is suggested, even though an experienced clinician should validate the results to ensure their reliability. The most popular markerless system, the Microsoft Kinect v1, is the first 3D camera whose affordable price made it accessible to almost all consumers. One of its innovations was that the sensor was suitable for gait assessment outside the laboratory, becoming a portable device[106-108]. Soon after, Microsoft launched its system with a hardware improvement, Kinect v2, and enhanced software, Kinect for Windows SDK 2.0. This system can detect the skeleton more accurately and track the 3D position of 25 joints up to 6 subjects simultaneously[109]. This camera can track the skeleton through Artificial Intelligence (AI). This feature briefly identifies body segments and joints centres, providing the movement's joint kinematics and spatiotemporal parameters accurately. The Microsoft Research team's algorithm can identify the correct position of anatomical landmarks because it was made out of a randomized decision forest algorithm using a subset of 100,000 depth scans of a variety of movements, including kicking, dancing, driving, running, walking[110].

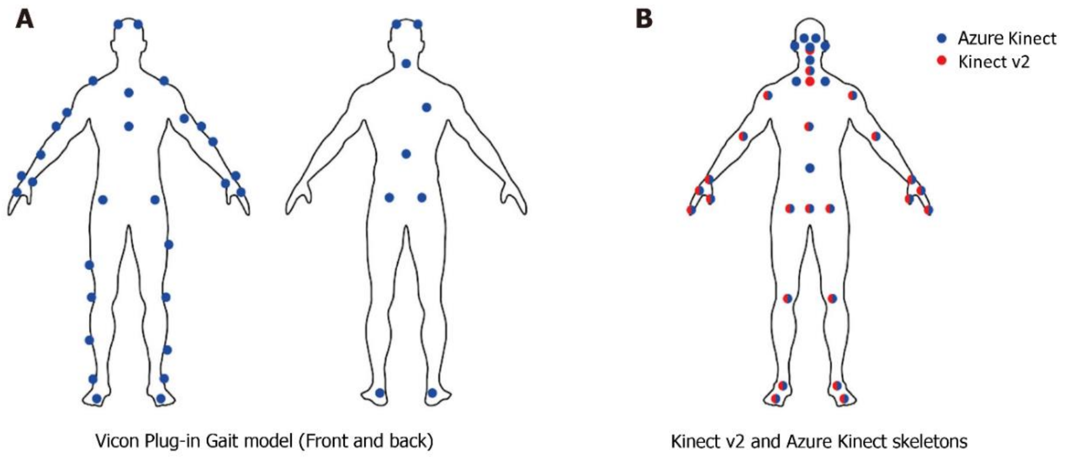


Figure 1: *Markers setup for Vicon and markerless caption for Kinect cameras. A: Markers setup for Vicon; B: Markerless caption for Kinect cameras.*

In recent years, several studies investigated the reliability of Kinect v1 and v2 to evaluate if these devices could be used as an alternative to the multi-camera motion capturing systems. Several contexts were examined, such as walking on a treadmill or executing physical exercises statically[111]. Wang et al.[112] examined the differences between Kinect v1 and v2 of twelve different physical exercises execution and their human pose estimation. The results showed a better accuracy to recognize joints and body rotation for Kinect v2 than Kinect v1. Capecci et al.[113] investigated the accuracy of Kinect v2**,** by evaluating the ability to recognize joints and segments while playing dynamic exercises for low back pain rehabilitation. The results highlighted high reliability to recognize timing characteristics of physical exercises and reproduce dynamic features similar to a stereophotogrammetric system[114,115]. Microsoft ended Kinect v2 production[116] in favour of new technology, the Azure Kinect DK. The latter, compared to other commercially cameras, offers significantly higher accuracy[117]. Unlike the previous, the Azure Kinect employs a Body Tracking SDK able to track up to 32 joints for multiple users, as shown in Figure 1b; it includes more joints, *i.e.*, anatomical landmarks such as eyes, ears, nose and lips. Albert et al.[117] accomplished gait analysis with both Microsoft Kinect v2 and Azure Kinect and then compared the data with those of Vicon system. The results showed high accuracy of both cameras, Microsoft Kinect v2 and Azure Kinect, but the latter showed better accuracy for spatial gait parameters. Figure 2 shows gait parameters of Microsoft Kinect and Azure Kinect in comparison to the Vicon system**.** Walker View (Tecnobody®- Dalmine, Italy) is a treadmill whose base includes eight load cells that allow the system to detect the user's spatiotemporal parameters. The presence of a Microsoft Kinect 2 camera automatically identifies anatomical landmarks using AI. The system is connected to a 49" LCD Monitor for the biofeedback and the virtual reality. Its advantage is the fully automatic and non-invasive approach, which is also an improvement in sport and rehabilitation research and practice. During the testing phase the patient/athlete can auto select the preferred walking speed or choose the Speed Control feature that adapts the treadmill speed to user's step velocity. In addition to the gait analysis, the Walker View can also perform run analysis, an especially useful evaluation for athletes. Regarding the training area, the patient can perform the Gait Trainer program where the software, through visive and acoustic feedback, helps him to improve his walking. Furthermore, the Walker View, thanks to the Smart Gravity system, can be used for patients with severe walking deficits unable to stand on their own. This system consists of a mechanical support to which a sling worn by the patient is connected. It can simulate a walk in the pool by selecting the appropriate weight reduction as if it were hydro-kinesitherapy.

Table 1. Studies investigating the reliability of IMU sensors

References	Sensor / position	Comparison system	Results	Outcomes
Qiu S. 2016 [118]	3 magnetic angular rate and gravity (MARG) / thigh, shank, and foot	Vicon	Position accuracy of 0.3%, the Δ XY radial distance error of 0.82% and the distance error of 0.27%, position error of 0.4%.	The combination of distributed wearable sensors with the Denavit–Hartenberg convention resulted in a promising tool for tracking lower limb movements.
Sprager S. 2015 [119]	1 multi-sensor platform integrated into a smart garment / knee	N.P.	Good activity discrimination can be achieved based RMSE and SD from flexible sensor, acceleration and gyroscope data.	Preliminary results show that walking, running, stairs climbing can be discriminated based on the data collected.
Cresswell KG. 2017 [120]	4 Shimmer3 sensor nodes / all sides of the shank	N.P.	The results of the fixed effects models highlighted the discrepancies between front–back mounting versus inner–outer mounting.	For y-axis gyroscope data, the variation is mostly influenced by mounting location. Mounting location should not vary but if it has to vary, it is better for it to vary between inner and outer leg mounting locations.
Fusca M. 2018 [121]	1 IMU / posterior CoM	Elite (BTS)	Mean absolute percentage error of: Stride time is 5.7%; Cadence is 4.9%; Step's length is 5.6%; Step's speed is 13.5%.	The use of IMU at CoM presents a good reliability for carrying out ambulatory, long-term, and ecologic kinematic of gait analysis.
Saggio G. 2020 [122]	7 IMU / pelvis, thighs, shanks and feet	Vicon	Joints ROMs RMSE and ICC PCC > 0.75 Reliability all the ICC > 0.975.	IMUs sensors showed a high reliability on joints' movement and walking test.

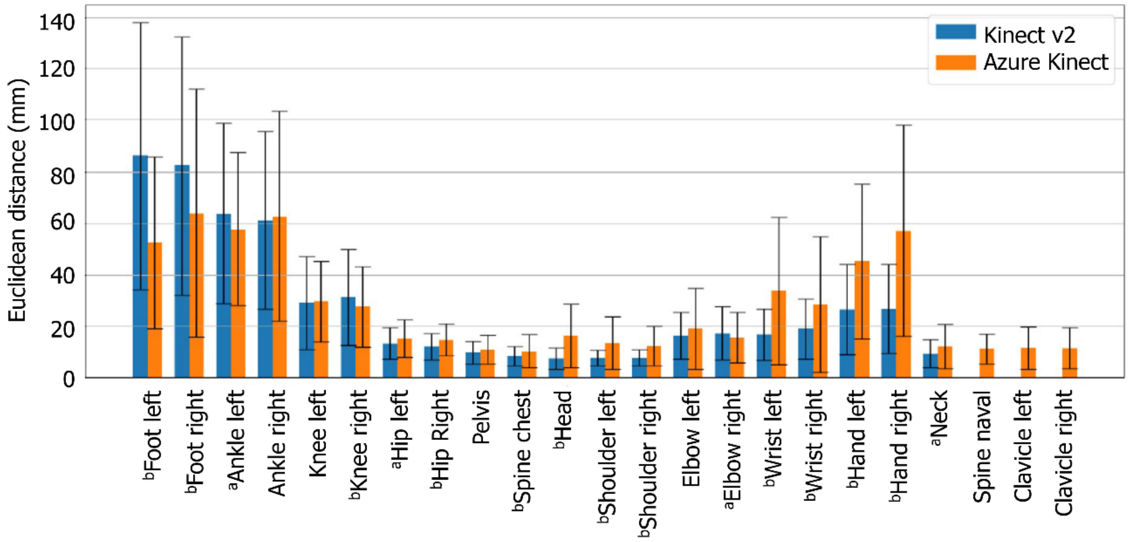
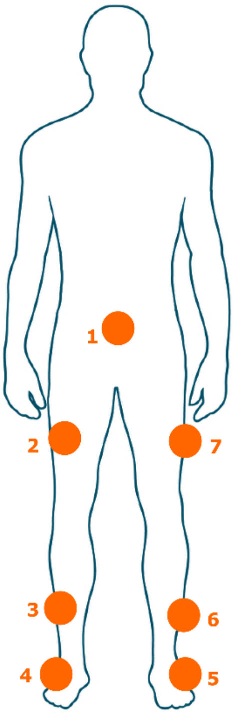


Figure 2: *Spatial agreement of Microsoft Kinect and Azure Kinect cameras with respect to the Vicon system. Errors are represented as means ± SD of the 3D Euclidean distances between according joints.* $^{a}P < 0.05$, $^{b}P < 0.01$.

Miniaturized inertial measurement units (IMUs) are a new generation of lightweight, small, and inexpensive systems embedding 3D accelerometers, gyroscopes, and magnetometers, which can offer new chances for the assessment of motor functions. IMUs can track in real-time the kinematic parameters of anatomical segments to estimate the gait cycle[118]. Although evaluation protocols are not homogeneous, several studies estimated the possibility of assessing the gait analysis through IMUs[119,120,123-125], as reported in Table 1. Fusca et al.[121] recruited ten volunteers on which they placed markers for motion capture using Elite (BTS) System, and IMU sensor placed anteriorly and close to the body's centre of mass (CoM). The authors stated that it is preferable to place the IMU sensor posteriorly between the superior anterior iliac spines since abdominal breathing could lead to artifacts. Four walking trials were simultaneously recorded at a self-selected speed by blindly comparing the two systems. The stride time had a mean absolute percentage error of 5.7% and the cadence 4.9%, for IMU. The mean absolute percentage errors were 5.6% and 13.5% in the step length and step speed measurement, respectively. Therefore, results assess the excellent reliability of IMU sensors to measure spatiotemporal parameters of human gait. The Italian Company Captiks Srl developed a innovative system based on inertial-sensor, Movit System[122], which allows measuring gait parameters by positioning the IMUs through elastic bands on different lower leg landmarks as shown in Figure 3. The company compared the results obtained from Movit System and Vicon optoelectronic system. According to the statistical analysis of the data on joint ROM reported by Cuesta-Vargas et al.[126] and Poitras et al.[127], the authors agreed on the excellent accuracy and test-retest reliability of IMUs on joint movement and walking tests. IMUs can encounter some drawbacks: these devices are placed on the human body through elastic bands, but unpredictable vibration artifacts can occur if the wearables are not firmly and adequately fixed. This represents an important issue since the artifacts are in the signal's frequency band, so not removable by filtering. Besides, misplacement of the sensors and movements that could cause the sensors to slip can lead to wrong measurements and make the exam inconclusive[121]. The main differences between the mentioned systems can be found in Table 2.



Sensor	Anatomical landmarks
1	Pelvis L5 level
2	Right thigh at mid-height of the femur
3	Right shank over the malleolus
4	Right foot in the dorsalis pedis
5	Left thigh at mid-height of the femur
6	Left shank over the malleolus
7	Left foot in the dorsalis pedis

Figure 4: *Body position of the seven inertial measurement units of Movit System.*

Table 2: Main features of motion analysis systems

Motion analysis systems	**Capture system**	**Anatomical landmark**	**Recording system**
Optoeletronic Measurement System	Stereoscopic 3D	Passive or active markers placed	Multi- IR cameras with stroboscopic LED
Microsoft Kinect	Time of Flight (ToF) method	Markeless	1 RGB - IR Camera
Inertial Measurement Unit (IMU)	9 Degree of Freedom (DOF)	Sensor placed with elastic band	Microprocessor processing raw data

Considering that three-dimensional motion capture systems are rather expensive, different low-cost methods have been developed during recent years. For instance, Kinovea is a free 2D software for computers valid to evaluate human motion and measure kinematic parameters. This software can accomplish evaluation without markers, although marker placement may improve its reliability[128]. Several studies tested Kinovea software[129-132] in different environments with good results: Damsted et al.[128] investigated its ability to detect hip and knee joint kinematics during running; Elwardany et al.[133] investigated the cervical spine range of movement in the sagittal plane while Mathew et al.[134] evaluated the software's ability to correctly detect ankle, knee, and hip joints movement during gait cycle phases. Kinovea only needs a camera and eventually some markers, although it requires an experienced clinician to use it. Once the movement is recorded, the clinician, in post-production, places the virtual anatomical landmarks over the joint centres or the markers physically positioned on the user. Unlike Microsoft Kinect, Kinovea does not have the appropriate software for the skeleton tracking system, so accurate marker placement or precise location of virtual anatomical landmarks is required to evaluate the movement correctly, otherwise, the results may not be valid. The main literature limitations for Kinovea concern the absence of a standard protocol for video analysis and marker placement[133,134]. The study conducted by González et al.[131] compared the inter/intra-rater Kinovea reliability to detect lower limb's joint angles during walking with the measurement of a 3D marker-based system (Vicon). The results showed significant differences in the hip, knee and ankle angles with a ± 5° difference for hip and ankle angles, ± 2.5° for knee angles. According to McGindey et al.[135], 2° or less of error is considered acceptable in clinical evaluation. Errors between 2° and 5° are also reasonable, although the data should be interpreted cautiously. Errors over 5° could mislead the interpretation. To conclude, as reported by Littrell et al.[136], the use of Kinovea could lead to high error for pelvis and foot measures during the stance phase of the gait cycle. However, the software is reliable when inspecting other kinematic parameters of walking such as joint angles[137], especially for sports environments or dynamic conditions where sophisticated systems could be impossible to be used.

Recently, applications (app) for smartphones have been developed to measure gait parameters. Researches, clinicians, and coaches can employ these applications to evaluate joint angles immediately. Unlike the previously mentioned systems, mobile applications are portable, cheaper, and easy to use. Although there is a lack of scientific studies investigating their reliability, the possibility of quickly measuring posture and joint angles in ordinary circumstances makes these applications compelling. Coach's Eye (TechSmith Corp) is a mobile app for the 2D motion analysis evaluation, able to collect gait parameters in patients and healthy individuals[138], although it was specifically designed for coaches and trainers to assess athletic performance. The app computes joint angles and their variations by a digitized goniometer without applying any marker on the body. The videos can be recorded on frontal and sagittal planes and inspected, frame by frame, going forward or backward. An online video database allows comparing the recorded videos with those of other athletes. However, only a few studies compared the app's data with the 3D motion analysis systems during sports tasks. Mousavi et al.[139] investigated the Coach's Eye app reliability and validity to measure lower limb kinematics during treadmill running by comparing its outcomes with those of a conventional 3D motion analysis system (Vicon).The authors recruited 20 healthy female recreational runners who wore 16 reflective markers for the 3D comparison. The subjects had to run on a treadmill at a self-selected speed. Concerning the validity, the results showed only a difference in kinematic measurements of 1-2 degrees compared to Vicon, specifically for hip, knee, ankle, and rearfoot at touchdown and toe-off for sagittal plane movements. The authors also stated that ankle angle at touchdown and knee angle at toe-off were not accurate., reporting a bias ranging from 4 to 20 degrees. Furthermore, Coach's Eye demonstrated valid test-retest reliability for all joint kinematic data, in agreement with Krause et al.[140] who reported high reliability of the application during the squat execution. The authors recommended the use of Coach's Eye to record and assess sagittal plane lower-limb joint kinematics and rearfoot in/eversion at touchdown, hip, ankle, and rearfoot eversion at toe-off. Nevertheless, given its ease of use and low cost, it would represent a manageable tool for sports coaches who frequently evaluate athletes.

Electromagnetic motion acquisition systems consist of a series of receivers that measure their position in space and transmit it to a nearby receiver. They are based on the electromagnetism principle: the emission source produces an electromagnetic field, and the sensors send the signal via cable to the processing unit, then the computerized system calculates sensors' position and direction in space based on these signals. For example, Polhemus and Ascension are two of the most popular companies producing electromagnetic motion systems[141,142]. This system finds application in evaluating a single fine movement, such as taking an object with the hand, which has high accuracy and a low margin of error compared to camera-based systems[143]. However, complex movement, such as walking, could be challenging can be difficult to examine. For this reason, the application is less suitable for clinical and sports movement analysis, such as gait analysis or technical sports gestures. Conversely, the entertainment industry exploits its high accuracy to reproduce the movement executed by a performer over a digital character[144]. Recently, Polhemus enabled localization of medical instruments through the trackers, especially for image-guided therapy[145]. The application of electromagnetic systems can be notably valid to enhance the medical students' skills, such as the use of endoscope and surgical instruments, tissue manipulation, use of precision tools, and other procedural skills before operating on patients.

In summary, the optoelectronic system is undoubtedly the gold standard for motion analysis, although modern markerless options might overcome some disadvantages and offer a valid alternative for outdoor examination. The strength of markerless systems relies on testing more users in shorter times and less equipment than the marker-based system. The markerless approach is more suitable for sport and rehabilitation purposes rather than diagnostics. Another way to capture human motion is by IMUs, lightweight devices easy and comfortable to be used almost everywhere. Finally, software or mobile application is applied, especially in athletic contexts where sophisticated tools collide with sport practice.

Gait Analysis In Prevention And Health Promotion

Gait analysis is recognised as a suitable tool for the human movement research, commonly used in biomechanical laboratories to assess the ability to walk in those with specific motor disabilities[146-149], often due to conditions as severe developmental motor impairments[150], spinal cord damage[151], amputees[152], orthopedic surgery[153], strokes[154] and cerebral palsy[155]. Specifically, clinical gait analysis can be classified into two levels of examination: a first level which deals with the clinical evaluation of the lower limb impairments by collecting data from spatiotemporal parameters, kinematics, and kinetics of locomotion; a second level which involves the use of dynamic electromyography, during gait, to evaluate the neuromuscular activity[156]. For the purely medical use, the SIAMOC (Italian Society of Clinical Movement Analysis) proposes these guidelines: 1) in cerebral palsy, the use of gait analysis, combined with an expert clinical evaluation, can influence the planning of functional surgery; 2) in adult brain injuries, the use of gait analysis can influence the orthopaedic surgery, neuromuscular blocks or rehabilitation programs; 3) in patients wearing lower limb prostheses, it might be useful for choices regarding the construction of the prosthesis and the planning of general models of rehabilitation[157]. Information deriving from this evaluation allows to increase diagnostic accuracy, differentiate diagnosis and severity, and help in decision-making about the treatments. Evidence demonstrates the efficacy of 3D gait analysis in defining gait problems, their causes, and the appropriate treatments (*e.g.*, surgery against non-surgical treatment or type of surgery). However, gait analysis continues to be a helpful tool partially exploited. The literature is not yet robust regarding using this system even outside clinical contests. Therefore, motion capture is limited to clinical examination, *i.e.*, orthopaedic, neurological, or surgical, not considering the possibilities deriving from daily life evaluation. Prevention and health promotion science could exploit gait analysis to avoid that a simple dysfunction develops into an actual disease. What would happen if orthopaedic patients performed this exam as a routine examination rather than in sight of surgery? For instance, according to Meireles et al.[158], the early stages of knee osteoarthritis are challenging to detect, but altered biomechanical conditions may contribute to its onset[159-162]. This study evaluated knee contact forces and the relation with external knee moments reporting that mechanical loading was quite equal for osteoarthritis subjects respect to normal ones. These results highlight the possibility that other causes (*e.g.*, spatiotemporal parameters, hip or ankle kinematics) might occur to develop osteoarthritis and therefore, gait analysis might be considered in disease management since current treatments offer limited benefits[163]. Several contests can benefit from an accurate exam guiding clinicians towards the best decision based on patients' needs. Pathologies involving walking abnormalities that afflict the central nervous systems are highly variable, and several different motor patterns can be altered. In cerebral palsy subjects, gait analysis investigated the common altered gait patterns, including toe-toe gait, stiff knee gait, jump knee gait, crouch knee gait, and several abnormalities. However, each subject presents a unique mixture of compensatory movements so, gait analysis can help clinicians recognizing the primary deformities and how they affect the musculoskeletal[164]. While the use of this approach in cerebral palsy has been widely investigated, there is less evidence in other neurological conditions. Gait analysis among spinal cord-damaged populations can help establish individualized interventions to enhance walking, improving muscle strength, coordination, proprioception, and postural control. Specifically, Murphy et al.[151] highlighted how gait analysis could provide specific information to clinicians to deal with spasticity management, *i.e.*, botulinum toxin-a injection; best orthotic selection, *i.e.*, hinged or rigid; surgery, *i.e.*, joint fusion; or establish the well-suited rehabilitation program [165]. In orthopedic contests, this exam can enhance understanding the subject's functional capacity reduction before surgery and, in the same way, indicate the elements that need to be improved following the surgery[166]. The fear of moving after surgery is often present in patients[167]; digital support, in this case, can help the patient understanding that within a specific range of movement, *e.g.*, walking for 500m or walking at speed 2km/h, will not suffer further pain and will not negatively affect recovery.

The use of gait analysis in the early stages of many pathologies could suggest re-educational intervention to reduce surgery later. Therefore, patients should be first examined through markerless systems and proceed to in-depth marker-based analysis when necessary, as reported in Figure 4, with improved time and cost-efficiency.

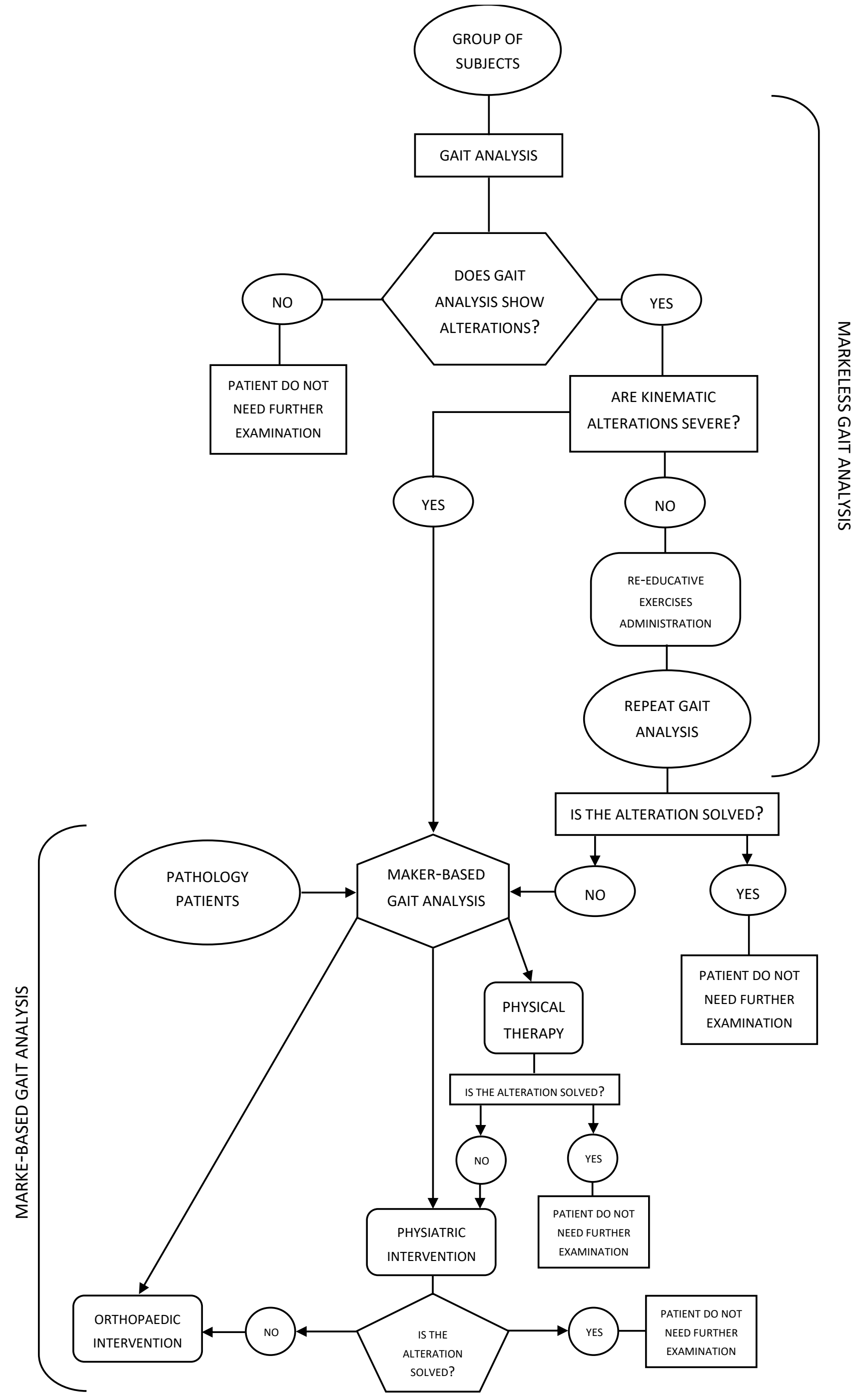


Figure 4: *Flow chart of the gait analysis approach levels. A guide explaining when it is enough a markerless gait analysis and when it is needed a marker based gait analysis.*

Computerized Analysis Of The Spine

Rasterstereography is a non-invasive method used to measure 3D spine deformities by analysing the back's surface topography on triangulation principles[168,169]. It was developed by Hierholzer and Drerup[170-172] in the 1980s as a valid alternative to radiography, and over the years, it has shown its high reliability in various studies[173-

175], Table 3 shows the main differences among these studies. The system reconstructs a 3D spine model by inspecting specific back's concavity and convexity beside collecting precise anatomical landmarks as the vertebra prominence and the lumbar dimples. The rasterstereography is commonly used to assess the presence of scoliosis, but it can efficiently evaluate other parameters as cervical lordosis, thoracic kyphosis, lumbar lordosis angles and pelvic obliquity [176,177]. Since this system is a non-invasive method, it can perform several measurement repeated over time with high reliability, which can reduce the use of radiography[168]. Krott et al.[178] provided a meta-analysis of 19 eligible studies whose aim was to investigate the validity and reliability of this system applied over a group of patients and healthy subjects with different spinal dysmorphisms or paramorphisms. The results stated high validity levels by being compared with the radiological imaging specifically to evaluate subjects' scoliosis, lumbar lordosis and thoracic kyphosis angles. The easiest accessibility of rasterstereography can spread through evaluating common health problems among children, adolescents[179], and adults, such as non-specific back pain and postural insufficiencies[180-183]. Several studies assessed its reliability and validity in the static upright position both in children and healthy adults, while recently, it was investigated the use of rasterstereography from static to a dynamic system. Michalik et al.[175] compared the dynamic rasterstereography of the spine under dynamic conditions, *i.e.,* walking, with the static measurement of the spine through the same system. Several differences were present between static and dynamic conditions about the trunk inclination, kyphotic angle at 2 *km/h*, general lordotic angles and lordotic angles specifically while increasing walking speed. There were no differences for the surface rotation between static and dynamic measurements. März et al. [184] used rasterstereography to investigate the influence of different occlusal positions on spine and body posture. Ten spinal and body postures have been compared (*i.e.,* trunk inclination, pelvic tilt, kyphotic and lordotic angles), in six different occlusal positions, only three parameters were found to differ. The authors concluded that a plausible explanation could be represented by neuromuscular compensation for body balance and posture on trigeminal proprioception[185]. Dental occlusion can provoke postural alteration specifically in masticatory muscles suggesting a neurophysiological connection between the stomatognathic system and other muscles[186,187]. The rasterstereography field of application involves screening programs, *e.g.*, early diagnosis and monitoring of scoliotic and scoliosis attitudes, lumbar hyperlordosis, dorsal hyperkyphosis, and all pathological conditions of the back; postural evaluation and musculoskeletal problems; design and verification of ergonomic and orthopaedic devices (ergonomic insoles, bites, prostheses, orthoses); support to therapeutic programs and postural re-education. Formetric (DIERS Medical Systems, Chicago, IL) is a rasterstereographic technology for evaluating the spine and posture that does not present any contraindications or side effects. It emits parallel lines of light over the back's surface and, by analyzing the distortion of those lines, it reconstruct a 3D image of the spine. The optical scan detects the anatomical landmarks (C7 or prominent cervical vertebra, sacrum, lumbar dimples), the symmetry of the spine and the rotation of each segment. Three different versions are currently available on the market: Formetric Basic, Formetric Basic 4D, and Formetric Basic 4D Motion. Formetric Basic produces a 3D analysis of the spine and posture, but it does not allow to perform a dynamic one. Formetric 4D can acquire image sequences, automatically processing average values, with a duration of the detection sequences even greater than 1 minute and the possibility to acquire up to 10 images per second. The newest version of this system is the Formetric 4D Motion, which can accomplish a dynamic analysis of the whole body and the skeletal system during a step execution or treadmill walking, due to the possibility to acquire up to 24 images per second. The high sampling rate allows excluding effects due to spontaneous postural oscillations or breathing. Once the exam has been performed, the system produces a report about physiological alterations of the spine both in the frontal and in the sagittal plane, degrees of vertebral rotation, pelvic tilt, and antero-retroversion.

Table 3: Studies investigating the reliability of rasterstereography to evaluate the spine

References	Aim	Coort	Results	Conclusion
Mohokum M. 2010[173]	To determine reproducibility of rasterstereography for kyphotic and lordotic angles, trunk length, and trunk inclination	51 healthy volunteers	Cronbach-α for the intratester-reliability of the kyphotic angle ICT-ITL (max.) between 0.921 and 0.992. The intertester-reliability for the same parameter is 0.979 (95% CI).	The reliability revealed good results, both for intratester and for intertester reliability of rasterstereography in kyphotic and lordotic parameters trunk length and trunk inclination.
Guidetti L. 2013[174]	To determine intra- and interday reliability of spine rasterstereographic system Formetric 4D with and without reflective markers.	26 healthy volunteers with markers (M), 26 healthy volunteers without markers (NM)	In M group, for intra- and interday reliability coefficients were 0.971, 0.963, and 0.958 (ICC) and 0.987, 0.983, and 0.985 (Cα) for trunk length, kyphotic angle, and lordotic apex, respectively. In NM group, they were 0.978, 0.982, and 0.972 and 0.989, 0.991, and 0.991 for trunk length.	The presence of the markers is not necessary for the intraday evaluations and can play a disturbing role for the interday evaluations, because of the repositioning process.
Michalik R. 2020[175]	To study the spinal and pelvic position under dynamic conditions and compare it to static measurements using a rasterstereographic system.	121 healthy volunteers (56 females; 65 males)	Trunk inclination (5.31° vs. 6.74°), vertebral kyphotic angle (42.53° vs. 39, 59°), and surface rotation (3.35° vs. 3.81°) increase under dynamic conditions ($p < 0.001$). Trunk shows significant changes during walking compared to static conditions ($p < 0.001$).	The spinal posture differs between females and males during standing and during walking. Rasterstereography is a valuable tool for the dynamic evaluation of spinal posture and pelvic position.
Albertsen IM. 2018[180]	To investigate whether the clinical Matthiass test can be objectified by means of dynamic rasterstereography in children.	101 healthy children	Cluster analysis identified two groups with different postural performance levels during the modified Matthiass Test. Low performers showed a higher increase in backward lean, kyphosis and lordosis (4°–5°, respectively) compared to high performers.	Modified Matthiass Test applied with Rasterstereography can discriminate between low and high posture profile among children.

Mobile application and wearable devices for posture management

PostureScreen Mobile (PSM) (Trinity, FL, USA) is an app that guides clinicians in rapidly identifying anatomical landmarks and posture assessment. Without the use of reflective markers, the app estimates the subject's posture using digitized anatomical landmarks. It exploits the device's camera to take a picture of the subject from frontal and sagittal planes. Once the picture is taken, the clinician place digital anatomical landmarks on the picture to produce an evaluation of the misalignment of the landmarks on the coronal and sagittal planes, as reported in Figure 5. Therefore, the app provides a file report that indicates possible posture misalignments. In the frontal plane, it inspects head, shoulders, hips tilt, and horizontal translation; in the sagittal plane, it evaluate the shift forward or rearward of the head, shoulders, hips and knees. Szucs et al.[188] tested the app in healthy young adults. Based on the results, the PSM app is a valid method to assess human posture within and across raters specifically when used with defined procedures and markers. For intra-rater reliability, results showed a good to excellent reliability (>0.75). For the angular variables, results showed a moderate to good reliability (0.50–0.75). In contrast with the previous study, Hopkins et al.[189] investigated the intraclass correlation coefficient of postural analysis between PSM app and Vicon 3D analysis. The results showed a significant bias in postural measurements in the frontal and sagittal with the PSM app, while the intraclass correlations were similar in most of the measurements between the two systems. These data suggest caution using the PSM app when highly accurate postural assessments are necessary. Instead, innovative use of this technology is proposed by Iacob et al.[190], which tested the PSM app to evaluate dental occlusion anomalies. Both static and dynamic occlusion were evaluated. Firstly, the subjects were divided according to normal or abnormal occlusion; assessing only statical differences ($p<0.05$) for the angle of head deviation. Secondly, the dental occlusion has been examined for each type of movement, subjects were divided into groups sorted by the presence or absence of interferences or premature contacts. Head deviation angle differences were found between normal and abnormal occlusion groups, suggesting a possible correlation between static occlusion and posture. Authors stated the PSM app reliability to inspect pathological occlusion interactions on body posture. Moreover, depending on the degree of postural alteration, the clinician can direct the patient toward correction therapy before the postural abnormalities become definitive and harm the musculoskeletal system[190].

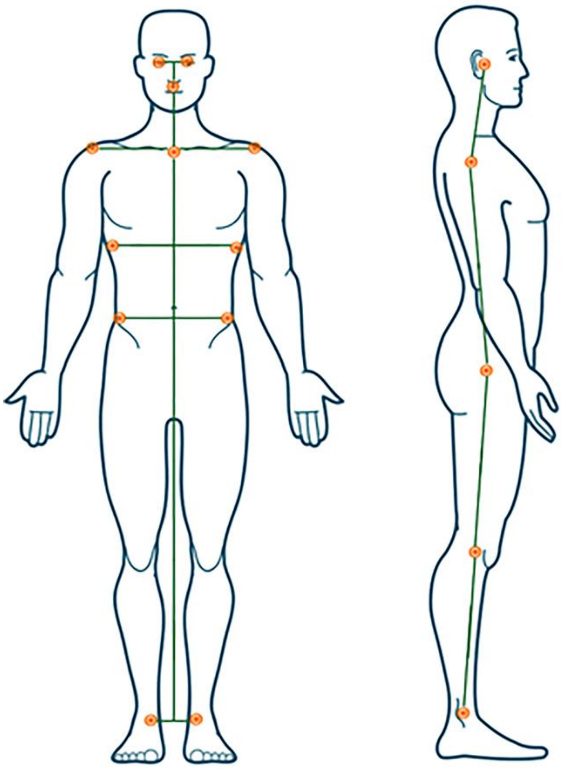


Figure 5: *Body position of the digital landmarks of PostureScreen Mobile, frontal and side view.*

Among innovative technologies, the growing reliability of wearable devices is noteworthy. Wearable devices joined the everyone’s daily lives, from the healthy individuals to older adults and those with chronic diseases[191,192]. These devices can quantify the movement schemes of all type of subjects in real-world settings. The wearables versatility over different populations type will contribute to investigate and understand the daily gait patterns for both walk and run[193]. The use of wearables is constantly expanding, especially in the field of gait analysis[194], post-operative rehabilitation[195,196], diagnosis and treatment of musculoskeletal disorders (*e.g.,* scoliosis, kyphosis, lordosis)[197,198], and posture management in the workplace[199]. In the context of posture analysis, wearables offer a low-cost and easy-to-use tool that provides real-time feedback for correcting workers' posture and reducing postural pain onset. Poor posture can lead to musculoskeletal disorders or spinal complications. It is well established that long sitting hours in front of computers cause pain, usually at the back. Abyarjoo et al.[200] proposed a wearable system for office workers that alarms the subject when he assumes a wrong posture. The Upright Go 2, following the success of its previous release (Upright Go), is a wearable device whose goal is to manage posture daily by promoting self-correction[201]. The device is about 48mm large, lightweight, and with a battery that lasts up to 35 hours. It can be applied to the back using hypoallergenic adhesives or worn with a unique necklace that ensures that the device stays on the back. It is equipped with multiple sensors that perceived if the subject slouches, and in this case, it will emit vibrations that stimulate the subject to regain a correct posture. The Upright Go 2 provides an app to monitor the progress over time, suggesting workouts to maintain the correct posture. Future studies about whether the subject would maintain a correct posture even after the device is no longer used would be an interesting prospect.

Overall Considerations

In recent years, a wide variety of technologies to study human movement has emerged, ranging from 3D visual software to wearable devices with almost imperceptible weight. The increase of technological devices has made it possible to expand the field of biomechanical assessment not only to the clinical environment but also to re-educational, sports and everyday life contexts. However, rapid technological development risks providing tools that are often not sufficiently validated. For example, the study conducted by Yoong et al., published just in November 2019[202], reports wearables that are no longer in production. For a device to be considered valid in the scientific field, it must comply with some strict parameters, and above all, it must maintain the reliability of its measurements constant. The evaluation of posture, movement, and gait and their deviations from physiological conditions are increasingly helpful in the clinical setting to diagnose musculoskeletal pathologies and in daily life to reduce the incidence of pain and disorders. As reported in Figure 4, this approach involves subdivisions based on the patient's criticality levels. Concerning gait analysis, a markerless system is a valuable tool for first-level screening as fully automatic and non-invasive, allowing to quickly evaluate many patients without stressing them with lengthy procedures. This first step streamlines the use of a marker-based system, making it available to more complex cases.

Similarly, the rasterstereography system, intended as a first-level approach, allows inspecting the back's topography leaving the second-level approach to radiographs, minimizing the need for repeat X-rays. In clinical practice, these approaches help in planning treatment, personalized rehabilitation programs, and surgical solutions. In everyday life, they give the possibility to remotely follow the patients, monitor progresses, and collect data on a large scale of users. As reported in Table 4, different systems serve different purposes, suggesting the need for a general scheme to direct the operator towards the most suitable analysis system to prefer.

Table 4: Application outline of each system

		Vicon	**Microsoft Kinect**	**IMU**	**Rasterstereography**	**Kinovea**	**PostureScreen**	**Coach's Eye**
Field of application	Clinical	High	Medium	Low	High	Low	N.A.	N.A.
	Sport	High	High	Medium	N.A.	High	N.A.	Medium
	Posture	High	High	Low	High	High	Medium	Low
	Surgery	High	N.A.	N.A.	Medium	N.A.	N.A.	N.A.
System potential	Accuracy	High	High	Medium	Medium	Medium	Medium/Low	Medium/Low
	Reliability	High	High/Medium	Medium	High	Medium	Medium/Low	Medium/Low
	Validity	High	High/Medium	Medium	High	Medium	Low	Low
	Reproducibility	Low	High	Low	High	Medium	Low	Low
Other characteristic	Outdoor	N.A.	Available	Available	N.A.	Available	Available	Available
	Markers/Sensors	Required	N.R.	Required	N.R.	N.R.	N.R.	N.R.
	Time required	High	Low	Medium	Low	Low	Low	Low
	Cost	High	Medium	Low	Medium	Low	Low	Low

Conclusion

This review highlighted the main applications of novel electronic devices in motion and posture analysis, describing their strengths and weaknesses. From the comparison of these systems, some of the mentioned devices have the potential to be used in clinical practice, sports, and healthcare prevention. Therefore, it is suggested that the scientific community might embrace an improved biomechanical approach through these new currently available tools for a tailored evaluation of patient's characteristics. The future of biomechanical research is a fast, fully automatic, non-invasive, and repeatable approach further away from human-dependent errors.

Chapter 3

Application of non-invasive methods in musculoskeletal research

The growing field of musculoskeletal health has progressively embraced non-invasive diagnostic and analytical methods, driven by the need for efficient, patient-friendly, and accurate approaches. This chapter analyses the diverse non-invasive techniques employed in a series of studies, ranging from advanced imaging technologies like thermography and rasterstereography to cutting-edge applications of machine learning in posture analysis. The overarching goal is to elucidate how these methods collectively contribute to a deeper understanding and more effective management of musculoskeletal health, particularly in the context of posture and movement analysis.

3.1 Infrared thermography

Infrared thermography (IRT) has emerged as a pivotal tool in the analysis of musculoskeletal disorders, offering a unique, non-invasive lens through which physiological changes associated with these conditions can be observed and quantified, Figure 3.1. Leveraging its ability to detect and visualize temperature variations on the skin's surface, IRT provides insights into underlying inflammatory processes, muscle overuse, and other pathological changes in musculoskeletal tissues. This method is particularly valuable in identifying asymmetrical thermal patterns, which are often indicative of musculoskeletal imbalances or injuries. For instance, in conditions like arthritis or tendonitis, affected areas may exhibit higher temperatures due to increased blood flow and metabolic activity. Similarly, in cases of muscle strain or injury, IRT can reveal cooler areas corresponding to reduced muscle function. The non-contact nature of IRT allows for a comfortable patient experience, making it an ideal choice for repeated assessments over time, which is crucial for monitoring the progression or resolution of musculoskeletal disorders. Its application extends from clinical diagnosis to rehabilitation settings, where it aids in evaluating the effectiveness of therapeutic interventions and in tailoring treatment plans based on the individual's specific thermal profile. The integration of IRT into musculoskeletal disorder analysis thus represents a significant advancement, offering a rapid and efficient approach to detecting and monitoring these conditions.

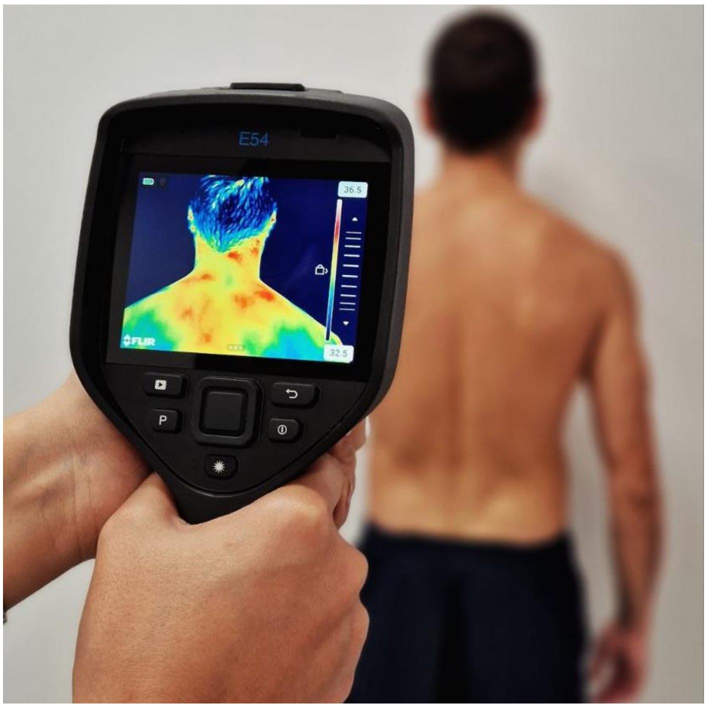


Figure 3.1: *Thermography application for the analysis of the neck thermal alterations.*

3.2 Rasterstereography

Rasterstereography stands out as a highly effective, non-invasive tool in the field of musculoskeletal disorders analysis, particularly valued for its precision in spinal and postural assessments, Figure 3.2. This technology operates by projecting a grid of light onto the back of the patient and capturing the distortions of this grid to create a detailed three-dimensional image of the spine and torso. The strength of the rasterstereography lies in its ability to provide accurate measurements of spinal curvatures, vertebral rotations, and postural deviations, which are crucial in diagnosing and monitoring conditions such as scoliosis, kyphosis, and other spinal deformities. Its ability to conduct repeated measurements without exposure to radiation makes it an ideal choice for monitoring the progression of spinal disorders, especially in patients where frequent assessment is necessary. Additionally, its application extends to the ergonomic assessment and occupational health fields, where it aids in identifying and correcting postural misalignments that could lead to or exacerbate musculoskeletal issues. Through its detailed and patient-safe approach, rasterstereography significantly enhances the capability to evaluate and manage a range of musculoskeletal disorders, providing valuable support in both clinical and research settings.

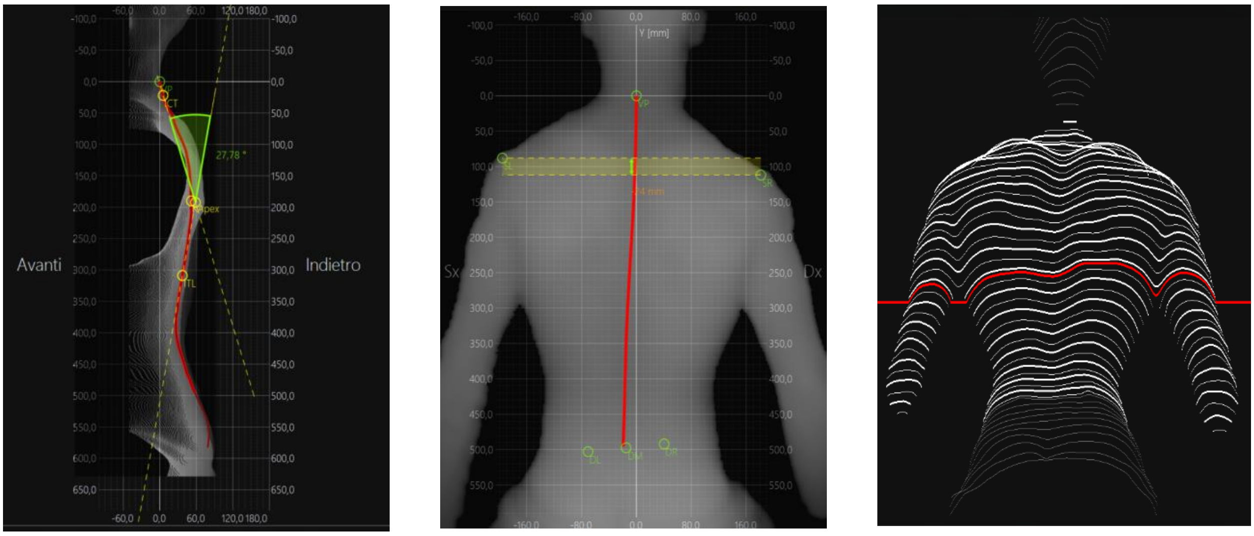


Figure 3.2: *Rasterstereography analysis of the sagittal (first), coronal (second) and transverse (third) planes of the back.*

3.3 Markerless Cameras

The integration of 3D markerless camera systems in the analysis of musculoskeletal disorders represents a significant leap forward in biomechanical assessment and diagnostics. This advanced technology, by capturing and analyzing human movement without the need for physical markers attached to the body, offers a non-invasive way for evaluating gait, posture, and joint biomechanics. Its applicability in musculoskeletal disorders is particularly noteworthy in the context of dynamic movement analysis. For instance, in assessing conditions such as osteoarthritis, gait abnormalities, or sports-related injuries, 3D markerless cameras provide detailed insights into joint kinematics, helping clinicians identify abnormal movement patterns, asymmetries, and compensatory strategies that might be contributing to pain. This technology is valuable in monitoring the progression of disorders and the effectiveness of treatments, whether in rehabilitation or athletic training scenarios. The high-resolution data obtained enables comprehensive analysis of musculoskeletal function in an unrestricted environment, such as on sports fields, thereby offering a more accurate reflection of real-world movement patterns in competitive contexts. The non-invasive nature of 3D markerless systems ensures patient comfort and compliance, making these cameras an essential tool in modern musculoskeletal and sports research.

Figure 3.3: *Markerless camera for the analysis of human movements*

3.4 Mobile Applications

The advent of mobile applications like PostureScreen and APECS for posture analysis has introduced a highly accessible and user-friendly dimension to the assessment and management of musculoskeletal disorders, Figure 3.4. These applications utilize smartphone technology to assess and analyze body posture, offering immediate feedback and detailed postural evaluations. Their ease of use enables not only clinicians but also individuals to engage in regular posture assessments, fostering greater awareness and proactive management of postural deviations that could lead to musculoskeletal issues. In clinical settings, these apps aid healthcare providers in swiftly pinpointing potential problem areas, such as misaligned spines or asymmetries in the joints of the upper and lower arms, which often precede conditions like chronic back pain or muscular imbalances. The visual and quantitative data provided by these applications facilitate a better understanding of the posture, allowing for more targeted treatment plans. By enhancing the accessibility of posture analysis, mobile applications such as PostureScreen and APECS become crucial in preventive healthcare and early intervention, thanks to their ease of use and swift operation.

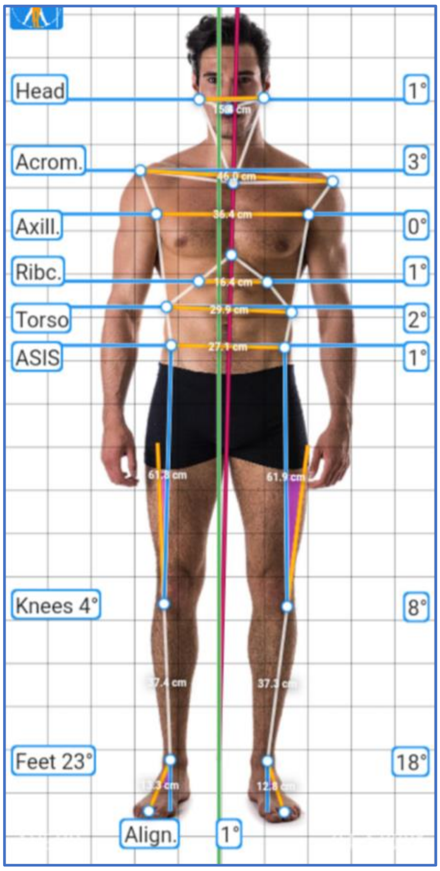


Figure 3.4: APECS mobile application for the analysis of human posture

3.5 Machine Learning algorithms

The integration of machine learning models into the analysis of musculoskeletal disorders marks a transformative advancement in biomechanical and postural assessment, Figure 3.5. These state-of-the-art models connect the power of artificial intelligence to accurately track and analyze human movement in real-time, using data captured from standard photo or video inputs. Their application in musculoskeletal disorder analysis is groundbreaking, especially in identifying and quantifying subtle abnormalities and compensatory mechanisms in movement patterns that may not be easily discernible through traditional assessment methods. By providing detailed biomechanical insights with high accuracy and efficiency, machine learning models like MediaPipe, PoseNet, and MoveNet are redefining the landscape of musculoskeletal diagnostics and therapy, supporting the way for more personalized, data-driven treatment strategies. Their strength lies in their ability to provide real-time, detailed analyses of joint kinematics, body alignment, and gait patterns, which are crucial in diagnosing and monitoring a wide array of musculoskeletal conditions. From identifying subtle postural deviations that could lead to chronic pain to analyzing athletic movements for injury prevention, these tools enhance the understanding of how musculoskeletal disorders manifest in motion. Their non-invasive nature ensures patient comfort and compliance, while their efficiency in processing large datasets makes them invaluable in both clinical practice and research. Collectively, they open new frontiers in personalized treatment approaches, offering objective insights that can guide effective therapeutic strategies and contribute to the advancement of musculoskeletal healthcare.

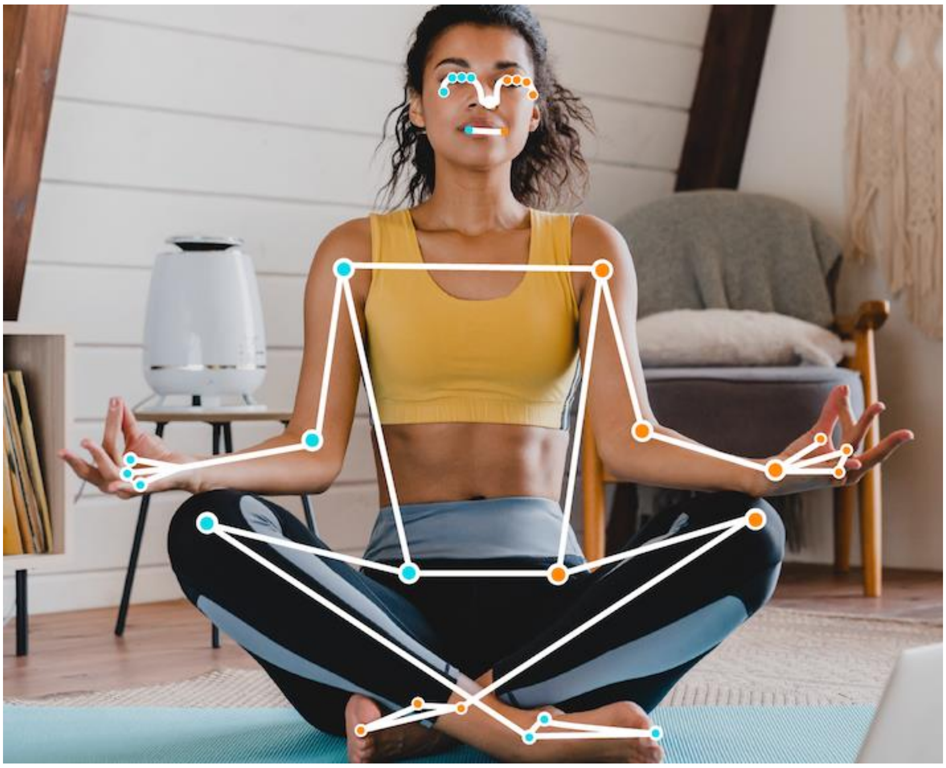


Figure 3.5: *MediaPipe Pose application for the human pose detection from a photo.*

Thermography and rasterstereography as a combined infrared method to assess the posture of healthy individuals

Federico Roggio [1,2], Luca Petrigna [1], Bruno Trovato [1], Marta Zanghì [1], Martina Sortino [1], Ermanno Vitale [3], Lucia Rapisarda [4], Gianluca Testa [5], Vito Pavone [5], Piero Pavone [6], Michele Vecchio [7], Giuseppe Musumeci [1,8,9,*]

[1] Department of Biomedical and Biotechnological Sciences, Section of Anatomy, Histology and Movement Science, School of Medicine, University of Catania, Via S. Sofia 97, 95123, Catania, Italy.

[2] Sport and Exercise Sciences Research Unit, Department of Psychology, Educational Science and Human Movement, University of Palermo, Via Giovanni Pascoli 6, Palermo, 90144, Italy.

[3] Occupational Medicine, Department of Clinical and Experimental Medicine, University of Catania, Via Santa Sofia, 87-95123 Catania, Italy.

[4] Spine Unit, Cannizzaro Hospital, Catania, 95123, Italy.

[5] Department of General Surgery and Medical Surgical Specialties, Section of Orthopedics and Traumatology, AOU. Policlinico-Vittorio Emanuele, University of Catania, Via Santa Sofia 78, 95123 Catania, Italy.

[6] Pediatric Clinic, Department of Clinical and Experimental Medicine, University Hospital A.U.O. "Policlinico-Vittorio Emanuele" of Catania, Catania, Italy.

[7] Department of Biomedical and Biotechnological Sciences, Section of Pharmacology, University of Catania Rehabilitation Unit, "AOU Policlinico G. Rodolico", Catania, Italy.

[8] Research Center on Motor Activities (CRAM), University of Catania, Via S. Sofia 97, 95123, Catania, Italy.

[9] Department of Biology, Sbarro Institute for Cancer Research and Molecular Medicine, College of Science and Technology, Temple University, Philadelphia, 19122, PA, United States

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Introduction

In recent decades, functional assessment of the trunk has increased for both clinical and biomechanical research due to financial and clinical issues. Health institutions demand increasingly reliable and reproducible methods to evaluate a large number of people without harmful effects. According to the Global Burden of Diseases report, musculoskeletal alterations are a leading causes of years lived with disability among young adults [3]. Noninvasive screening methods can detect a specific alteration before the individual experiences discomfort or pain. Rasterstereography is a spreading method that uses light detection and ranging technology (LiDAR) to estimate physiologic or pathological posture. Due to its excellent intra- and interday reliability [174], it can be considered as a first-level approach when dealing with a large scale of users.

Infrared thermography (IRT) is a noninvasive method valid to investigate the physiological response of the body to different stimuli, e.g., physical activity [203], rheumatic diseases [204], and metabolic alterations [205]. Body temperature alteration is a natural indicator of compromised underlying conditions [206] and muscle demand [207]; IRT is an auxiliary method that supports the diagnosis process by discriminating altered skin temperature and, therefore, physiological processes. We believe that a combined infrared method (CIM) formed by a 3D camera to analyze human movement and thermography to assess thermal symmetry may represent an objective method to analyze the musculoskeletal system, Fig 1.

In the present study, we employed a CIM to evaluate the back surface of healthy individuals without postural deformities to provide reference data to the research community. Furthermore, we analyzed the correlation between these two noninvasive infrared systems.

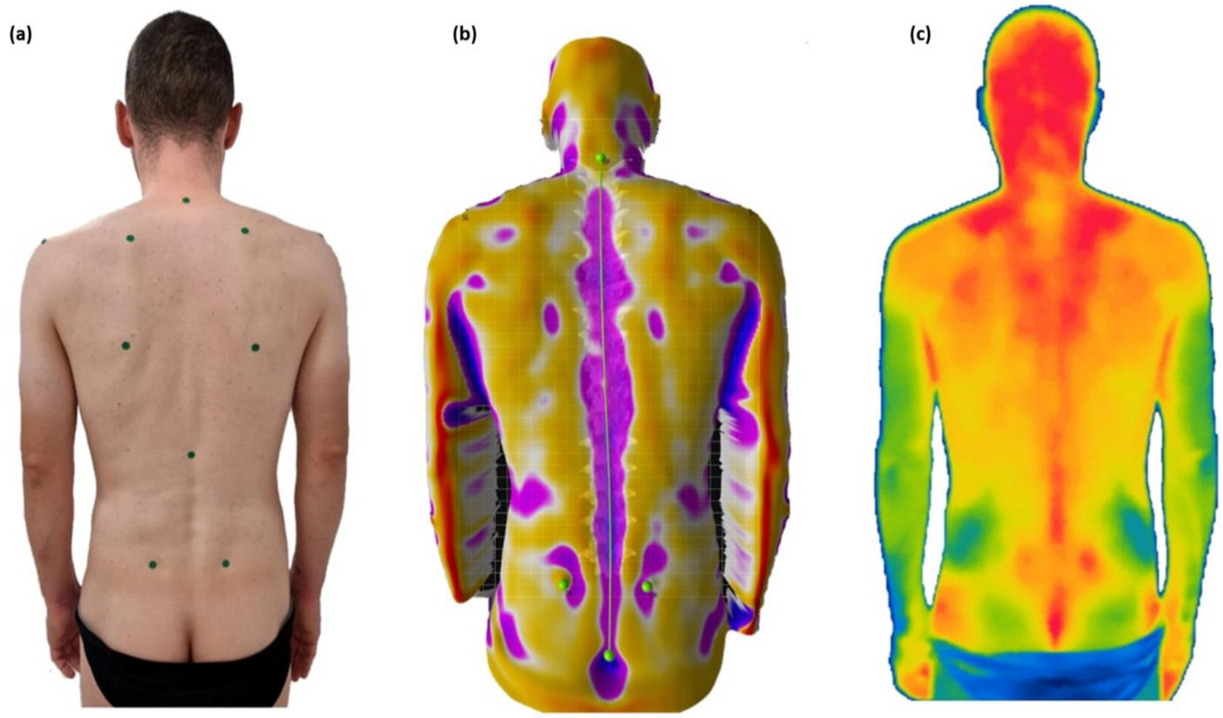

Fig 1: *Combined infrared method representing a normal photo of the individual (a), a rasterstereographic representation (b) deriving from Spine 3D system, and infrared thermography (c) obtained from Thermal Studio Pro version number:1.9.38.0.*

Results

The characteristics of the participants, expressed as mean and standard deviation for body height, body weight, and body mass index (BMI), are presented in Table 1.

Table 1: Anthropometric measures of the sample

	Males	Females	t-test
	Mean ± SD	Mean ± SD	
Age (years)	28.8 ± 6.21	29.6 ± 7.50	< 0.001
Height (cm)	177.37 ± 7.16	163.48 ± 7.20	
Weight (kg)	70.40 ± 7.82	56.19 ± 5.82	
BMI	22.34 ± 1.55	21.01 ± 1.44	

t-test according to Student t-test

Rasterstereography

The surface topography results of both the sagittal and coronal planes are reported in Table 2 and Fig 2 divided by gender; we discuss the results with a p-value < 0.05. On the sagittal plane, the male group shows a higher trunk inclination (31.38 ± 18.90 mm) compared to the female group (20.74 ± 19.95 mm) with a medium effect size (d = 0.55). There is a significant difference in cervical depth between males (43.67 ± 9.99 mm) and females (31.74 ± 7.76 mm) with a large effect size (d = 1.33). This trend is also respected for the cervical arrow, where males (56.97 ± 14.38 mm) have a higher value compared to females (38.73 ± 9.67 mm) with a large effect size (d = 1.49). Finally, the lumbar angle presents a lower value for males (36.39 ± 8.70 °) compared to females (47.56 ± 8.47 °) with a larger effect value (d = -1.30). On the coronal plane, we observed only a meaningful difference in shoulders obliquity between males (-7.23 ± 10.16 mm) and females (-2.91 ± 9.93 mm) with a medium effect size (d= -0.43). Finally, we also considered shoulders and pelvic torsion in the transverse plane. The results of the shoulders torsion are 0.34 ± 2.05 ° for males and 0.07 ± 2.32 ° (p= 0.634) for females with a small effect size (d= 0.12); the pelvic torsion results are -1.22 ± 2.97 ° for males and -1.81 ± 2.44 ° for females (p= 0.405) with a small effect size (d= 0.22).

Table 2: Rasterstereographic measures of the sagittal and coronal plane

	Males	Females	Sig. $^{+}$	Effect size (d) $^{++}$
	Mean ± SD	Mean ± SD		
Sagittal plane				
Trunk length	499.33 ± 29.79	444.94 ± 23.66	< 0.001 ***	**2.02**
Trunk inclination (mm)	25.53 ± 19.13	16.23 ± 16.64	0.047 **	***0.52***
Trunk inclination (°)	2.91 ± 2.14	2.09 ± 2.11	0.134	0.40
Cervical depth	43.77 ± 10.96	34.29 ± 7.04	< 0.001 ***	**1.03**
Cervical arrow	54.37 ± 15.16	40.32 ± 9.26	< 0.001 ***	**1.11**
Lumbar depth	53.37 ± 8.65	50.10 ± 7.01	0.110	0.42
Lumbar arrow	42.77 ± 11.62	43.01 ± 10.55	0.934	-0.02
Kyphosis angle	47.09 ± 9.33	44.85 ± 7.48	0.307	0.26
Lumbar lordosis angle	37.69 ± 8.89	46.49 ± 8.25	< 0.001 ***	**-1.03**
Coronal plane				
Trunk imbalance (mm)	-1.9 ± 6.14	-3.94 ± 6.83	0.225	0.31
Trunk imbalance (°)	0.21 ± 0.69	0.51 ± 0.89	0.144	-0.38
Shoulders obliquity (mm)	-8.23 ± 11.11	-1.68 ± 9.71	0.017 **	***-0.63***
Shoulders obliquity (°)	-1.26 ± 1.73	-0.31 ± 1.75	0.037 **	***-0.55***
Pelvic obliquity (mm)	2.73 ± 4.93	0.58 ± 4.51	0.080 ·	***0.51***
Pelvic obliquity (°)	1.64 ± 2.89	0.46 ± 2.62	0.101	0.43
Vertebral deviation RMS	2.47 ± 1.2	2.42 ± 1.20	0.878	0.04
Vertebral deviation min	-2.67 ± 2.41	-2.58 ± 2.16	0.883	-0.04
Vertebral deviation max	2.2 ± 2.22	2.81 ± 2.48	0.318	-0.26
Surface rotation RMS	4.57 ± 2.65	5.23 ± 2.66	0.332	-0.25
Surface rotation min	-3.22 ± 3.46	-3.42 ± 4.08	0.838	0.05
Surface rotation max	6.49 ± ± 4.23	7.45 ± 4.31	0.381	-0.22

$^{+}$ according to t-test for normal data and Mann-Whitney U for non-normal data · p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001; $^{++}$ Cohen's value, bold numbers indicate a large effect size between groups (d > 0.80). Bold and italic numbers indicate a medium effect size between groups (d > 0.50).

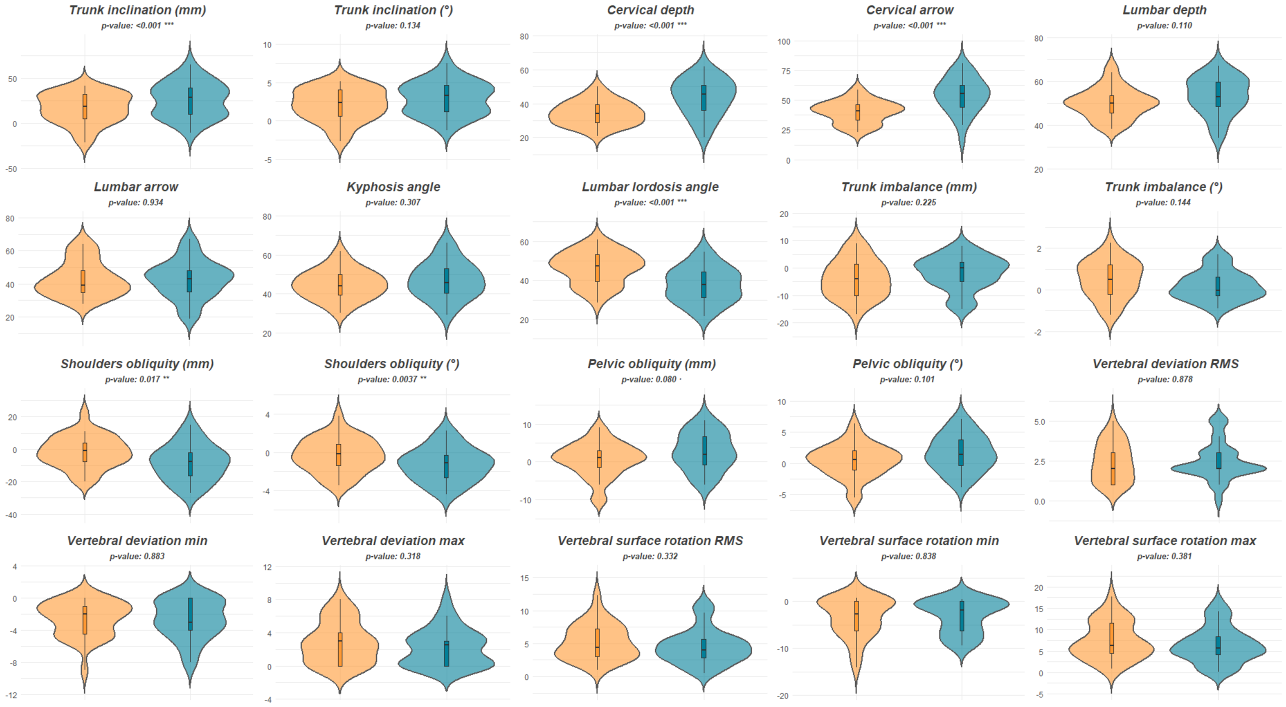

Fig 2 *Violin plots for the sagittal (first two lines) and coronal (last three lines) parameters. Orange represents the female group; blue represents the male group. Each violin plot shows inside the boxplot and the correspondent p-value, · $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.*

Infrared thermography

Males have a lower cervical temperature (33.83 ± 0.63 °C) compared to females (34.26 ± 0.84 °C) with p= 0.029 and a medium effect size (d= -0.58). Furthermore, the dorsal temperature of males (33.13 ± 0.71 °C) is lower compared to females (33.59 ± 0.97 °C) with p= 0.035 and medium effect size (d= -0.55). The lumbar temperature of males (32.76 ± 0.94 °C) and females (33.06 ± 1.23 °C) does not differ between the groups, with p= 0.273 and a low effect size (d= -0.27). However, the data distribution is different between the groups, Fig 3.

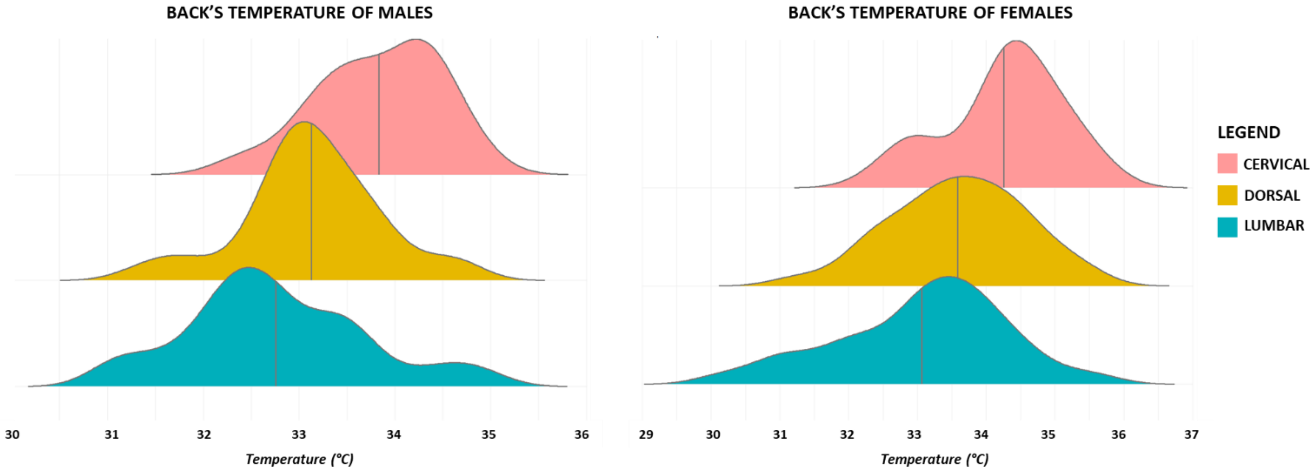

Fig 3 *Ridge plots of temperature distribution for males and females. The vertical line in each plot represents the mean temperature.*

Correlation between rasterstereography and infrared thermography

IRT measures have been correlated with rasterstereography measures to observe if a higher or lower skin temperature may reflect a correlation with back topography. The male group showed a negative correlation between lumbar temperature and trunk imbalance (°) (r= -0.42, p= 0.032); vertebral surface rotation RMS with cervical (r= -0.46, p= 0.010), dorsal (r= -0.60, p< 0.001) and lumbar (r= -0.50, p= 0.007) temperatures; vertebral surface rotation max with cervical (r= -0.45, p= 0.013), dorsal (r= -0.56, p= 0.001) and lumbar (r= -0.38, p= 0.043) temperatures. Meanwhile, they present a positive correlation between shoulders obliquity with cervical temperature (r= 0.58, p< 0.001) and with dorsal temperature (r= 0.45, p= 0.020).

The female group showed a negative correlation between lumbar temperature with lumbar lordosis angle (r= -0.50, p= 0.004). Instead, dorsal temperature is positively correlated with trunk imbalance (°) (r= 0.42, p= 0.022); lumbar temperature with trunk imbalance (°) (r= 0.43 p= 0.016); dorsal temperature with shoulders torsion (r= 0.43, p= 0.014).

Table 3: Parameters comparison of mean ± SD with other studies

	Males	Females	Degenhardt et al. [208]	Degenhardt et al. [209]	Michalik et al. [175] (Males)	Michalik et al. [175] (Females)	Wolf et al. [210]
Sagittal plane							
Trunk length	499.33 ± 29.79	444.94 ± 23.66	463.35 ± 33.38	466 ± 33.3	492.82 ± 28.43	452.38 ± 26.72	n.a.
Trunk inclination (mm)	25.53 ± 19.13	16.23 ± 16.64	25.49 ± 18.32	26.23 ± 17.66	n.a.	n.a.	25.7 ± 16.9
Trunk inclination (°)	2.91 ± 2.14	2.09 ± 2.11	3.09 ± 2.25	3.17 ± 2.18	1.89 ± 1.88	2.12 ± 2.40	3.2 ± 2.1
Cervical depth	43.77 ± 10.96	34.29 ± 7.04	n.a.	n.a.	n.a.	n.a.	n.a.
Cervical arrow	54.37 ± 15.16	40.32 ± 9.26	71.08 ± 19.67	74.42 ± 16.49	n.a.	n.a.	n.a.
Lumbar depth	53.37 ± 8.65	50.10 ± 7.01	n.a.	n.a.	n.a.	n.a.	n.a.
Lumbar arrow	42.77 ± 11.62	43.01 ± 10.55	36.62 ± 12.62	37.53 ± 12.18	n.a.	n.a.	n.a.
Kyphosis angle	47.09 ± 9.33	44.85 ± 7.48	47.23 ± 9.35	48.47 ± 8.32	44.58 ± 7.84	44.02 ± 8.64	44.2 ± 7.9
Lumbar lordosis angle	37.69 ± 8.89	46.49 ± 8.25	36.26 ± 8.53	35.42 ± 7.55	28.96 ± 7.67	37.36 ± 28.96	41.5 ± 9.2
Coronal plane							
Trunk imbalance (mm)	-1.9 ± 6.14	-3.94 ± 6.83	1.32 ± 7.16	1.29 ± 5.62	n.a.	n.a.	-2.6 ± 7.5
Trunk imbalance (°)	0.21 ± 0.69	0.51 ± 0.89	0.16 ± 0.85	0.15 ± 0.66	-0.08 ± 0.96	-0.07 ± 0.91	-0.3 ± 0.9
Shoulders obliquity (mm)	-8.23 ± 11.11	-1.68 ± 9.71	n.a.	n.a.	n.a.	n.a.	-7.3 ± 8.9
Shoulders obliquity (°)	-1.26 ± 1.73	-0.31 ± 1.75	n.a.	n.a.	n.a.	n.a.	-1.1 ± 1.3
Pelvic obliquity (mm)	2.73 ± 4.93	0.58 ± 4.51	-0.11 ± 3.39	-0.12 ± 5.13	n.a.	n.a.	-0.2 ± 2.2
Pelvic obliquity (°)	1.64 ± 2.89	0.46 ± 2.62	0.00 ± 5.78	-0.17 ± 2.92	-0.32 ± 3.34	-0.42 ± 2.79	-0.1 ± 1.1
Vertebral deviation RMS	2.47 ± 1.2	2.42 ± 1.20	5.53 ± 2.92	5.43 ± 2.49	5.07 ± 2.13	5.59 ± 2.32	n.a.
Vertebral deviation min	-2.67 ± 2.41	-2.58 ± 2.16	-4.73 ± 4.11	8.04 ± 5.13	n.a.	n.a.	-4.4 ± 3.6
Vertebral deviation max	2.2 ± 2.22	2.81 ± 2.48	7.86 ± 5.60	-4.62 ± 2.92	n.a.	n.a.	3.2 ± 3.0
Surface rotation RMS	4.57 ± 2.65	5.23 ± 2.66	3.74 ± 1.24	3.78 ± 0.93	3.54 ± 1.56	3.64 ± 1.62	n.a.
Surface rotation min	-3.22 ± 3.46	-3.42 ± 4.08	-4.38 ± 2.71	-4.51 ± 2.40	n.a.	n.a.	-3.9 ± 2.8
Surface rotation max	6.49 ± ± 4.23	7.45 ± 4.31	5.97 ± 3.51	5.68 ± 2.79	n.a.	n.a.	1.7 ± 1.9

n.a= not available, columns males (n= 85) and females (n= 90) represent our findings, Degenhardt et al. [208] (n= 30 M/F), Degenhardt et al. [209] (n= 30 M/F), Michalik et al. [175] males= 65, females= 56), Wolf et al. [210] (n= 100 females)

Discussion

This study aimed to present reference data on physiological posture standards of healthy individuals without spinal deformities using a CIM. Rasterstereography evaluated the back topography; the IRT measured the thermal emissivity of the back to assess muscle activity. These two methods have spread in recent years thanks to the ease of use and objective measures that can support the clinical practice of analyzing the spine and detecting underlying conditions not yet visible to the human eye, as claimed by two systematic reviews [211,212]. The demand for rasterstereography as a noninvasive method is increasing to reduce the burden of the healthcare system and reduce follow-up radiological measurements [213]. Similarly, IRT is providing valuable results in monitoring the body's response to external stimuli such as cryotherapy [214], whole-body vibration [215], and strength training [216].

Establishing a thermal profile has been one of the main topics since IRT was adopted for human diagnostic purposes. In the late 1980s, Uematsu et al. [217,218] tried to quantify the thermal symmetry of healthy individuals by studying the differences between both sides of the body. Even if these initial results were promising, the limitations of the tools of that period stalled its progression. Nowadays, different authors, through modern IR cameras, have attempted to classify different body areas among young adults. Chudecka and Lubkowska [219] analyzed the IRT of 100 males and 100 females (aged 20-23), finding that only the chest area had a higher temperature in females, while the other areas were warmer in males. The mean temperature of the upper back of males (33.92 ± 0.19 °C) is similar to our results for the cervical area (33.83 ± 0.63 °C). Marins et al. [220], aiming to present normative data of healthy Brazilian adults (mean age 21.6 ± 2.2), found a significant gender difference in the thigh region while there was no difference in the hands, leg, abdomen, and lower back, as our results. In another study, Marins et al. [221] accomplished the IRT in the early morning (7 a.m.) and late evening (7 p.m.) of military males and females. They found a gender difference in the morning thermograms, while no differences relative to gender were present in the evening collections.

We compared the results of the rasterstereography with four similar studies [175,208-210] evaluating the back of healthy individuals, as reported in Table 3. Our findings showed a general difference based on gender for almost all parameters of the rasterstereography of the sagittal plane; meanwhile, only three parameters of the coronal plane differed by gender. We found a great difference in cervical measures; males show an increased depth of the cervical area, a trend also respected for the lumbar depth. However, the lumbar lordosis angle appears to be greater for females, similar to the results of Michalik et al. [175]. Meanwhile, the lumbar lordosis angle of the males is similar to the results of Degenhardt et al. [208,209]. Although the trunk inclination of the females is similar to the results of Michalik et al. [175], the values of the males are similar only to the studies of Degenhardt et al. [11,12]. For the parameters of the coronal plane, the only similarities are in the pelvic obliquity of our females with the findings of Michalik et al. [175]. According to our findings, there is a significant difference in trunk length between males and females, which may explain some of the differences found in other parameters. This difference is likely due to the biological differences between males and females, as well as differences in their activities or occupations. The morphological characteristics of the body play an important role in determining its stability and posture [222]. We suggest that the differences in trunk inclination and sagittal curvatures, such as cervical depth and lumbar lordosis angle differences, are a response to the body's evolution and environment [223]. The increase in trunk inclination is essential for maintaining the center of gravity within the base of support, and men are usually found to have a larger sway amplitude compared to women [222]. Previous studies [224,225] have also observed gender differences in anthropometry, vertebral geometry, and strength of the neck and shoulder area, which may contribute to the observed differences in posture. For example, women generally have smaller vertebrae and weaker muscles compared to men. Our findings are consistent with these observations, as we found similar gender differences in both rasterstereography and IRT measurements.

Finally, we correlated the rasterstereography parameters with the IRT. Even if with moderate strength, the correlations reported are all statistically significant, meaning that they are unlikely to have occurred by chance. In the female group, when the lumbar lordosis angle increases, the lumbar temperature decreases. Studies have shown that the lumbar lordosis angle is genetically different between males and females, with females having a greater angle [226,227]. In our study, we observed a reduction in anterior imbalance, which was balanced by an increase in the lumbar lordosis angle. Since this is an anatomical aspect and not an acquired condition, it does not involve muscle activity, which results in lower metabolic activity in the underlying muscles, and thus a possible explanation for the negative correlation. The dorsal temperature was positively correlated with shoulder torsion. We suggest that wearing uncomfortable bras could lead to a constant postural defect, which may cause torsion of the shoulders. As Chen et al. [228] observed, different types of bras can restrict shoulder motion and cause discomfort. Therefore, the increased temperature may be related to a higher demand of the body to support the breast. Finally, also lateral trunk imbalance was positively correlated with lumbar and dorsal temperatures, suggesting that as the degree of trunk imbalance increases, the temperature in the lumbar and dorsal regions tends to increase. This may be due to an increase in muscle activity in the lumbar and dorsal regions to compensate for trunk imbalances, leading to increased metabolic activity and subsequent elevation of skin temperature in these regions. This phenomenon may also be related to the previous statement.

In our male group, shoulder obliquity was moderately correlated with cervical and dorsal temperature. Since they practice gym activities, we hypothesized that these positive correlations, i.e., as the shoulder obliquity increases, the temperature increases, could be explained by the higher muscular demand of the shoulders area. As males tend to work out their upper limbs more than females [229], this may contribute to the higher temperature in the shoulder region. Then, we observed a moderate negative correlation between cervical, dorsal and lumbar temperatures with both vertebral surface rotation RMS and maximum rotation. In scoliosis, the concave side is the side toward which the vertebrae rotate, and, as asserted by Kwok et al. [230], the concave side of scoliosis has a lower temperature. Our results highlight a trend, when the vertebrae rotation increases, the temperature decreases. However, it is important to note that these findings were observed only in the male group and should be interpreted with caution. Finally, we found that the negative correlation between lumbar temperature and trunk imbalance may be related to muscle imbalances caused by gym activities [231]. Although as a stand-alone consideration may be meaningless, when we also consider the valuable correlation between vertebral surface rotation and skin temperatures, it suggests that males may be at risk of spinal misalignment. Thus, a decrease in skin temperature may be associated with an increase in spinal deformities or muscle imbalances.

These findings suggest that different mechanisms may influence the relationship between skin temperature and back topography in males and females, potentially, potentially due to differences in muscle activation and blood flow regulation between the genders. However, more research is needed to fully understand the underlying mechanisms driving these correlations.

Currently, both rasterstereography and IRT are being studied in the evaluation and progression of scoliosis, even if there are still some concerns. The former is not sufficiently accurate to diagnose scoliosis, but as observed by different authors, it is making considerable progress in characterizing the typical signs of scoliosis, such as vertebral rotation [232], shoulder imbalance [233], and monitoring the progression of scoliosis [234]. The latter is yielding promising results for scoliosis evaluation [235], highlighting its feasibility for school scoliosis screening, a field where preventive care is required [236].

Aware of the impossibility of considering rasterstereography as a substitute for x-rays in the diagnosis of spinal pathologies [25], we support its strength as a screening tool, as reported by Rusnak et al. in the early identification of spinal deformities in 311 children [237]. Likewise, we support IRT as a complementary method for screening and preventing muscle injuries [238] and inflammatory processes [239]. Therefore, we believe that reference data from both screening techniques can support orthopaedic, rehabilitation, and clinical research toward a better distinction of red flags of spine deformities.

This study has some limitations. First, we observed a group of healthy adults with similar anthropometrics under 35 years of age, so the findings should be carefully interpreted when comparing them with pathological patients or old adults. Second, although the participants did not present any detectable posture alteration, it was not checked with diagnostic tools (x-rays or MRI), so there may be some minor posture alterations. Third, we did not analyze fat tissue, so even if individuals with BMI > 25 were not considered, we could not be sure that the temperature was the same for all the participants. Further studies are required to investigate the thermal changes associated with fat tissue percentage by conducting bioelectrical impedance analysis and considering different age ranges, e.g., adolescents and older adults.

We believe that this pioneering technique, a combination of infrared methods, will aid in elucidating the characteristics of posture alterations and muscle activity with a non-invasive, easy, and reliable method. Future studies could use it to study musculoskeletal pathologies and gait analysis and discover correlations between IRT and kinematics and kinetics.

Conclusions

A CIM composed of rasterstereography and thermography has been adopted to study the postural assessment of the back classified by gender. Males commonly present a higher trunk inclination, shoulder obliquity, cervical, and lumbar depth. Although the kyphosis angle is the same for both sexes, females present an increased lumbar lordosis angle. Females have a significantly higher temperature in the cervical and dorsal areas of the back compared to males, while the lumbar temperature is also higher in females but not statistically significant. The correlation between these two methods requires further investigation as it may help to better understand the complex mechanism of spine alterations and muscle activity asymmetry. This study is a significant contribution to knowledge on back topography and may be a reference for other researchers interested in using a CIM to evaluate postural alterations.

Materials and Methods

This cross-sectional study involved 175 healthy individuals (85 males and 90 females) aged 22 to 35 and analyzed the back surface with rasterstereography and thermography.

Participants were recruited voluntarily at the Research Center in Motor Activities (CRAM), University of Catania. We considered the age limit of 35 years to avoid confounding elements due to the incidence of age-related musculoskeletal disorders [3] or specific work conditions that can bias the data. Participants completed a questionnaire to collect general information about pathologies, allergies, medication use, recent surgery, regular menstrual cycle, sports played, and dominant limb. According to this information, the exclusion criteria were musculoskeletal disorders, history of scoliosis or spine alterations, acute back pain during the previous four months, recent surgery, altered menstrual cycle, BMI < 18.5 or > 25. The study was approved by the Research Center in Motor Activities (CRAM) Institutional Review Board, University of Catania (Protocol n.: CRAM-020-2021, 20 December 2021), in accordance with the Declaration of Helsinki. All participants provided their informed consent prior to participating.

Data collection

A LiDAR technology was used to assess the rasterstereography. The Spine 3D (Sensormedica, Rome, Italy) is a noninvasive 3D system that analyzes the spine in the three planes: sagittal, coronal, and transverse, with an excellent intra-day and inter-day reliability in almost all parameters [240]. A 3D camera embedded in the system evaluates the back with the time of flight method, with a resolution of 1920 × 1080 pixels and a frame rate of acquisition of 30 fps. A detailed explanation of all the parameters collected is reported in Table 4. The IR acquisitions were carried out according to the TISEM checklist [241] to ensure the quality of thermal images and reduce bias. IR images were taken with FLIR E54 camera (Wilsonville, OR, USA) camera with a detector resolution of 320x240 pixels and thermal sensitivity <0.04° C. The camera was placed on a tripod, positioned 1.5 m away from the individual in a room with a temperature of 24 ± 2° C and humidity of 50%; emissivity level was set at 0.98. Infrared thermography detects the radiance of a body; then, the algorithms present in these cameras convert the radiance into temperature values, thus providing the expression of the temperature of the body surface [242]. The participants were asked to rest for 15 minutes before the IR imaging was taken in order to allow for acclimatization. For both acquisitions, participants were instructed to stand upright with their back to the camera, arms by their side, without upper clothes, and buttocks slightly uncovered. For the rasterstereography acquisition, participants were instructed to place the heels on a line 110 cm from the camera, looking straight ahead. For the IRT acquisition, participants were instructed to stand upright with the arms slightly away from the trunk. The IRT camera was placed 150 cm away from the participant. Each of the thermograms was analyzed using FLIR Thermal Studio PRO software, version number: 1.9.38.0. The regions of interest were the left and right sides of the cervical, dorsal, and lumbar area, Fig 4. We strictly followed the suggestion from the practical guide of Ammer and Ring [243] to avoid possible bias in the study. Thermograms whose difference between the left and right side was > 0.3 °C were excluded [244].

Table 4: description of rasterstereography parameters

Sagittal plane	
Trunk length (mm)	The distance between VP and DM
Trunk inclination (mm)	The distance between two vertical lines passing for VP and DM
Trunk inclination (°)	The angle between the plumb line passing for VP and a vertical line connecting VP-DM
Cervical depth	The horizontal distance between the cervical apex and a tangent passing for KA
Cervical arrow	The horizontal distance between the cervical apex and a perpendicular line passing for KA
Lumbar depth	The horizontal distance between the lumbar apex and a tangent passing for KA
Lumbar arrow	The horizontal distance between the lumbar apex and a perpendicular line passing for KA
Kyphosis angle	The angle formed between the two surface tangent lines of the ICT and ITL
Lumbar lordosis angle	The angle formed between the two surface tangent lines of the ITL and ILS
Coronal plane	
Trunk imbalance (mm)	The lateral distance between two lines passing for VP and DM
Trunk imbalance (°)	The angle between the plumb line passing for VP and a vertical line connecting VP-DM
Shoulders obliquity (mm)	The distance between two horizontal lines passing for SR and SL.
Shoulders obliquity (°)	The angle between a horizontal line passing for SR and SL and a horizontal line perpendicular to the gravity line
Pelvic obliquity (mm)	The distance between two horizontal lines passing for DR and DL.
Pelvic obliquity (°)	The angle between a horizontal line passing for DR and DL and a horizontal line perpendicular to the gravity line
Vertebral deviation RMS	The RMS deviation of the midline of the spine from the direct connection VP-DM line
Vertebral deviation min	The maximum deviation to the left of the midline of the spine from the VP-DM line
Vertebral deviation max	The maximum deviation to the right of the midline of the spine from the VP-DM line
Surface rotation RMS	The RMS rotation in the axial plane of a spinous process when compared to the neutral pelvis

Surface rotation min	The maximum rotation to the left in the axial plane of a spinous process when compared to the neutral pelvis
Surface rotation max	The maximum rotation to the right in the axial plane of a spinous process when compared to the neutral pelvis
Transversal plane	
Shoulder torsion	The rotation in the transversal plane of the SR relative to a reference coronal plane perpendicular to the camera-projection axis.
Pelvic torsion	The rotation in the transversal plane of the DR relative to a reference coronal plane perpendicular to the camera-projection axis.

VP= Vertebra Prominent, DM=Dimple Midpoint, KA= kyphotic apex, ICT= inflection point between cervical and thoracic spine, ITL= inflection point between thoracic and lumbar spine, ILS= inflection point between lumbar spine and sacrum, SR= shoulder right, SL= shoulder left, DR= dimple right, DL= dimple left, RMS= root mean square.

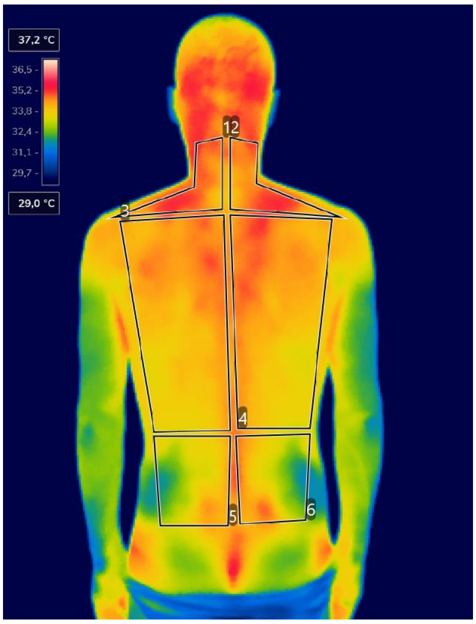

Fig 4 *Representation of IRT acquisition and polygon division of each back's area. Numbers 1 and 2 represent the cervical area, numbers 3 and 4 the dorsal area, numbers 5 and 6 the lumbar area.*

Statistical analysis

The data analysis was conducted using R Project for Statistical Computing (Vienna, Austria). The Shapiro–Wilk test verified the normality distribution, the Student t-test and Mann–Whitney U were used to determine whether any significant difference was present between males and females for rasterstereography and IRT imaging. Cohen's effect size (d) identified significant differences between the groups. Pearson correlation coefficients (r) were calculated to estimate correlations between rasterstereography and the surface temperature of the selected regions of interest.

Thermal profile classification of the back of sportive and sedentary healthy individuals

Bruno Trovato[1], Federico Roggio[1,2], Martina Sortino[1], Lucia Rapisarda[3], Luca Petrigna[1,*] and Giuseppe Musumeci[1,4,5]

[1] Department of Biomedical and Biotechnological Sciences, Section of Anatomy, Histology and Movement Science, School of Medicine, University of Catania, Via S. Sofia n°97, 95123, Catania, Italy

[2] Sport and Exercise Sciences Research Unit, Department of Psychology, Educational Science and Human Movement, University of Palermo, Via Giovanni Pascoli 6, Palermo, 90144, Italy

[3] Spine Unit, Cannizzaro Hospital, Catania, 95123, Italy

[4] Research Center on Motor Activities (CRAM), University of Catania, Via S. Sofia n°97, 95123, Catania, Italy

[5] Department of Biology, Sbarro Institute for Cancer Research and Molecular Medicine, College of Science and Technology, Temple University, Philadelphia, 19122, PA, United States

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1. Introduction

The implementation of new technologies that provide data for the analysis of the musculoskeletal system has allowed a wider understanding of human physiology both in static and dynamic conditions [245]. The current interest of the scientific community is growing in the directions of those technologies that do not expose the individual to harmful radiations [29]. It is possible to examine the human body during its movements with tools like inertial sensors, infrared cameras, stereophotogrammetry and marker-less motion analysis systems [29]. For the static analysis of the musculoskeletal system the non-harmful technologies comprehend rasterstereography, infrared cameras, wearable devices [246] and mobile application for posture assessment [247], 3D ultrasound imaging system [248], digital palpation device [249], Moiré topography [250] and infrared thermography (IRT) [251].

The interest of the scientific community for IRT as a complementary tool for the evaluation of the human body, and especially for the musculoskeletal system, is growing in the last decade [252-255]. This technique is easy to perform and it is non-harmful, highly reproducible [256], non-invasive and it does not require the contact with the patient. The IRT cameras use an advanced thermometer that detects the heat radiations of a body in an electromagnetic spectrum invisible for the human eyes [257].

The standard operating procedure to perform accurate and reliable thermographic measurements is the one proposed in 2017 by Moreira et al. [241] who redacted the Thermographic Imaging in Sports and Exercise Medicine checklist (TISEM) with all the variables to take into account when performing studies with infrared thermography, to minimize the risk of bias. With IRT it is possible to evaluate different of pathologies, selecting correct regions of interest (ROI) on the skin to analyze, from musculoskeletal diseases, such as rheumatoid arthritis [258], to breast cancer [259], psychophysiology and emotions [260]. Sport science is an interesting field of research where the IRT finds its application due to its versatility and the possibility of in-field use. Interestingly, IRT was employed with encouraging results as an indirect marker of muscle damage after an acute protocol of plyometric jumps in physically active men [261], as well as in the evaluation of professional athletes during competitions to achieve a better understanding of the thermoregulatory system during the performance [262]. To date, there are only a few studies that classified the thermal profiles of athletes in static conditions [263]. Collecting baseline data on the thermal profiles of the back of sport practitioners can help physician and trainers in adapting their approach to the sport and to enhance their health status maintenance [264]. As it was demonstrated by Côrte et al. [238] and Gomez-Carmona et al. [265] IRT has the potential to be a useful prevention tool for the reduction of the injury rate during a competitive season in professional athletes. Studying the thermal profiles of the back of different practitioners from various disciplines could possibly highlight thermal differences driven by the adaptation to the practiced activity.

Thus, the aim of this study is to assess and classify the thermographic profiles of the back of sport practitioners from different disciplines and compare it with those of sedentary healthy individuals.

2. Materials and methods

A sample composed of 160 voluntary healthy young adults was recruited, 75 males and 85 females. Prior to testing, all participants were informed about the study procedure, risks, and benefits and provided written, informed consent to participate in the study and to use their data. All participants gave their informed consent before participation. The study was approved by the local ethics committee of the Research Center on Motor Activities (CRAM), University of Catania (Protocol Number: Protocol n.: CRAM-020-2021, 20/12/2021), and it was conducted in accordance with the Declaration of Helsinki.

A researcher collected baseline information from each participant, including age (years), gender, height (cm), body weight (kg) and sport practiced prior to the thermal imaging acquisition. Furthermore, information related to their health status and sport background were also collected. Only healthy young adults were included and they were excluded if they presented physical acute (inflammation) or chronical conditions (chronic low back pain, scoliosis…). Inactive group (IN) was composed by young adults that didn't took part in any physical and sporting activity in the last year. The sport group was composed by participants that practiced in weight training (WT), individual sport (IS), team sport (TS) for at least 5 years. Furthermore, sportive participants were considered eligible for the study only if they reported an average of 3 sessions of training per week. The sports included in the TS group were soccer, volleyball and basketball with 31 participants, in the IS group were swimming, track and field, ballet with 40 participants, the WT group had 69 participants and the IN group comprehended 20 participants.

2.1 Instruments

All the thermographic measurements were taken with the FLIR E54 (Wilsonville, OR, USA) camera with a detector resolution of 320x240 pixels and thermal sensitivity <0.04°

C. The camera was placed onto a tripod, distant 1.5 m from the individual in a room with a temperature of 23° ± 2° C and humidity of 50%; camera emissivity level was set at 0.98. Three ROI were identified using the Flir thermal studio pro® software: cervical, dorsal and lumbar area. The ROI were delimited considering the vertebrae of the spine and excluding the upper limbs. The cervical ROI was delimited with a rectangle starting from the third cervical vertebra to the seventh one. The dorsal ROI of the body was delimited with a polygon from the first to the twelfth thoracic vertebra. The lumbar area was delimited with a polygon from the first to the fifth lumbar vertebra. The ROI were generated by one of the investigators adopting the original pictures in which it was possible to see directly the body. The ROI were double checked by a second investigator. No landmarks were adopted. The temperature scale was set between 26° C and 36° for all the evaluations. The identification of the ROI is presented in figure 1.

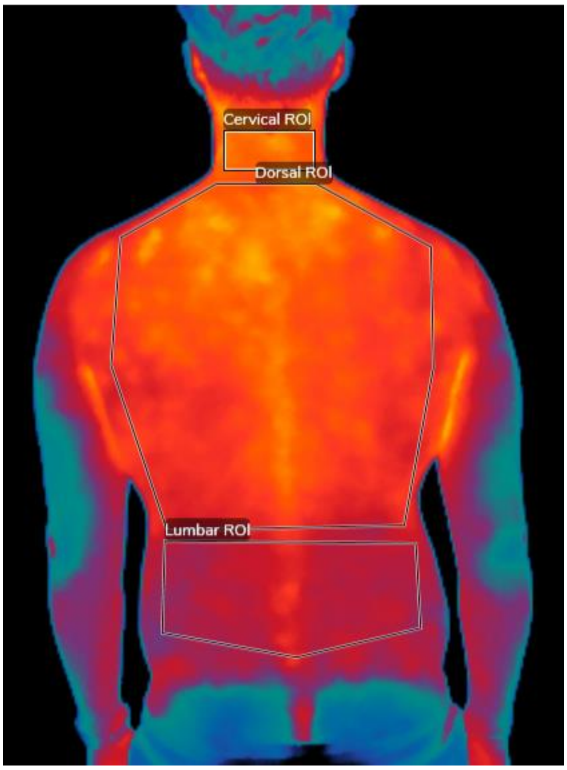

Fig 1. *Identification of the cervical, dorsal and lumbar ROI with Flir Thermal Studio Pro.*

All the participants had an acclimatization time of 20 minutes prior testing and the thermographic measurements were taken at morning, with no physical activity performed in the previous 24 hours. Considering the influencing intrinsic and extrinsic factors for the measurement of the skin temperatures (T_{sk}) with IRT [244] we applied the following exclusion criteria: presence of ointment on the skins surface of the selected ROI, assumption of anti-inflammatories, analgesic, contraceptive and anesthetic drugs 48 hours prior the measurements and caffeine consumption 3 hours prior testing.

2.2 Data analysis

The thermographic values analyzed were the averages skin temperature (T_{sk}) of the 3 ROI selected considering that the vast majority of previous literature on IRT analysis employed this method [266] and that other analysis methods are more feasible when physical activity is administered, and our sample was investigated at rest. For the anthropometric data, the Shapiro-Wilk test assessed the normality of the data. To discern significant differences between males and females, the Student's t-test was utilized. Cohen's d quantified the effect size between the groups. Inferential statistics comprised the Levene’s test to verify the homogeneity of the variance, the Mahalanobis distance verified the presence of multivariate outliers, the multivariate analysis of the variance (MANOVA) with the post hoc Tukey test was applied to detect significant differences between groups, Eta squared (η^2) evaluated the effect size. The linear regression has been applied to observe the effect of each variable on the temperature of the back and highlight any possible confounding effect. Significance was accepted at $p < 0.05$. All the statistical analysis were performed with R Project for Statistical Computing (Vienna, Austria).

3. Results

The anthropometric results are reported in Table 1. The MANOVA analysis resulted significant showing statistical differences for the cervical ROI ($p < 0.001$), dorsal ROI ($p = 0.0011$), and lumbar ROI ($p = 0.0366$) with $\eta^2 = 0.05$. The group with the higher temperature in the three ROI examined was the IN group, and the statistical analysis confirmed that there were significant differences between this group and the TS, IS, and WT group (figure 2). Table 2 shows the average temperature of group per each ROI and two-way MANOVA results.

Table 1: Anthropometric data of the sample

Parameters	Males		Females			
	Mean	SD	Mean	SD	t-test	Cohen's d
Height	176,32	8,1	162,99	6,0	< 0,001 ***	1,864
Weight	73,39	11,9	58,58	8,8	< 0,001 ***	1,415
Age	26,32	5,2	26,82	5,2	0,551	-0,097

**: p<0.05; **: p< 0.01; ***: p< 0.001*

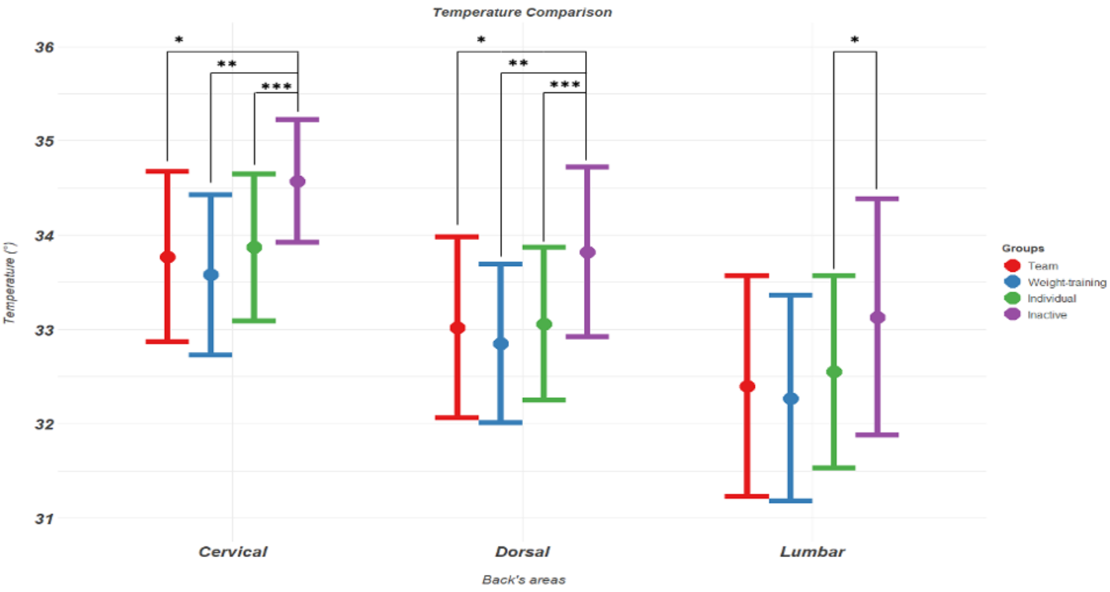

***Figure 2**. Box plot of the thermal differences between groups. *: p<0.5; **: p<0.01; ***p<0.001*

***Table 2**. Description of the average Tsk and MANOVA analysis of the four groups.*

ROI	*Groups*	*Mean*	*SD*	*p-value*
Cervical	Weight Training	33.8	0.9	0.0036 **
	Individual Sport	33.6	0.85	
	Team Sport	33.9	0.78	
	Inactive	34.6	0.65	
Dorsal	Weight Training	33.0	0.96	0.0011 **
	Individual Sport	32.8	0.84	
	Team Sport	33.1	0.81	
	Inactive	33.8	0.9	

Lumbar	Weight Training	32.4	1.17	0.0365 *
	Individual Sport	32.3	1.09	
	Team Sport	32.5	1.02	
	Inactive	33.1	1.25	

ROI: region of interest; *: p<0.05; **: p< 0.01; ***: p< 0.001

The highest temperature among sport practitioners was found in the TS group for the cervical, dorsal and lumbar ROI, but no statistically significant differences were found with other sport group. Figure 3 and 4 show the thermographic profile of the back of a participant from each group. The Tukey post hoc test for pairwise comparison showed statistically significant differences between groups; the results are presented in table 3.

Table 2. Statistical differences between group with Tukey post hoc test

ROI	Groups					
	IS-WT	TS-WT	IN-WT	TS-IS	IN-IS	IN-TS
Cervical	p= 0.696	p= 0.949	p= 0.002**	p= 0.487	p< 0.001***	p= 0.020*
Dorsal	p= 0.687	p= 0.998	p= 0.007**	p= 0.856	p< 0.001***	p= 0.013*
Lumbar	p= 0.927	p= 0.991	p= 0.096	p= 0.857	p= 0.043*	p= 0.242

ROI: region of interest; IS: individual sport; WT: weight training; TS: team sport; IN: inactive

For the cervical ROI significance was found between the IN and WT group (p= 0.002), the IN and IS group (p <0.001), IN and TS group (p= 0.020). The dorsal ROI resulted significant between the IN and WT group (p= 0.007), the IN and IS group (p< 0.001), IN and TS group (p= 0.013). The lumbar ROI showed significant differences only between the IN and IS group (p= 0.043).

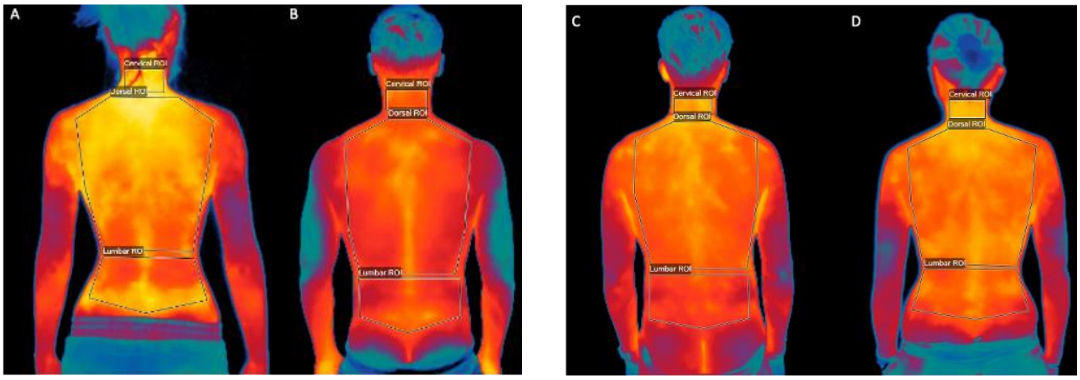

Figure 3. *Thermographic profile of a participant's region of interest (ROI) respectively of the IN (A), IS group (B), TS (C), and WT group (D).*

To examine the influence of each variable on the temperature, we conducted a linear regression with temperature for each area as the dependent variable and the group division as the independent one. To further understand these relationships and address potential confounding effects, we expanded our model to incorporate other relevant predictors: gender, height, weight, and age. The changes in the coefficients associated with the group variable levels were not significant for any of the three areas. These findings are detailed in the Supplementary material.

4. Discussion

The main finding of this study was that sedentary people present a statistically significant higher temperature of the three ROI of the back examined compared to team sport players, individual players and weight training practitioners. We found that the temperature followed the same pattern through the three ROI in all groups with the cervical ROI being the warmer one and the lumbar ROI the coldest one; moreover, we did not find any significant differences between male and female in all groups. To ensure no confounding elements skewed the results, we conducted multiple linear regressions. Introducing demographic predictors led to minor changes in the coefficients tied to the groups, and none showed a significant correlation with the temperatures. This underscores the group variable's impact on temperature variations. Notably, these relationships remained consistent, unaffected by potential confounders.

It is a well know topic in literature that physical inactivity is correlated, as a risk factor, to many different pathologies, from the metabolic to the musculoskeletal ones [267,268]. Physical inactivity is connected to a higher general prevalence of low back pain [269] and it is also correlated with neck pain [270]. It was found by Wu et al. [271] that a decrement in temperature was correlated with lower pain score reported by individuals with back pain using the numeric pain rating scale. In our sample the highest temperature in the three ROI examined was recorded in the sedentary group; this could be explained by the negative effects that physical inactivity has on the musculoskeletal system, especially in neck pain [62] and low back pain [272]. The average temperature of three ROI of the back in all groups followed the same pattern with a higher temperature for the cervical ROI, in line with another study analyzing the back of healthy individuals [273].

Currently, the available literature does not provide data for the definition of the average temperature of the back in sportive individuals to consider as baseline for thermal comparison with sedentary people or specific populations, e.g., chronic pathologies. Furthermore, the studies that investigated this issue, focused only the lower limbs [274-276]. However, the IRT is currently being adopted as a supportive method in the evaluation of different musculoskeletal pathologies [204,277,278]. In 2020 Lubowska et al. [279] compared children with scoliosis aged between 7 and 16 years with healthy matched control. The authors found that children with scoliosis presented thermal asymmetries especially in the thighs, upper back and chest. Although this study analyzed also the back of healthy individuals, as a control group, it is difficult to compare these thermographic data with ours, due to the huge difference in the age of the samples investigated; moreover, the cervical ROI in the Lubowska et al. study was not evaluated. Alfieri et al. [280] evaluated the temperature and pain tolerance in patients with chronic low back pain by comparing the differences with a healthy sample. The average temperature of the 19 healthy individuals considered as control group was 29.7 C° which is quite different from our results as we found an average of 33.8 C° in our sedentary group. This noticeable difference could be explained by the difference in the IRT camera used. We employed the FLIR E54 camera which has a better resolution and a greater accuracy than the one used by those authors (±2 C° instead of ± 1 C°). Furthermore, our sample is considerably younger than theirs (26.6 ± 5.31 instead of 47.8 ± 13.9 years), and mainly composed by sportive individuals. The baseline and the higher temperature may be the reflection of a more active muscle tissue. We also found that team sport players had an average higher temperature of the three ROI evaluated in comparison to other sportive individuals; however, the differences were not statistically significant.

Different factors can influence average T_{sk} [244] and physical activity is know to alter the thermal response of the body with a reduction in temperature after exercise [281] , due to the thermoregulatory response of sweat [282] and blood flow redirection to the muscles involved in the activity [283]. It is know that physical activity leads to enhancements in both increasing vessel quantity and diameter within the skeletal muscles, and these modifications in the vascular structure likely contribute to functional improvements and better blood circulation [284]. We surmise that the lower temperature of our sportive samples compared to the sedentary one might be due to the chronic adaptation to exercise that affects also the arteries [285], with a redistribution of blood flow from the superficial layers to the deeper skeletal muscles. This study presents some limitations. Firstly, although our sample was composed of participants practicing different sports at least 3 times per week, they were not professional athletes, so our findings could differ from other studies analyzing professional athletes. Furthermore, it was no possible to create smaller groups based on the specific sports limiting our findings to general and indicative information but providing feedback for future studies. Secondly, we evaluated a sample of healthy individuals only that not reported neck or back pain and we could not correlate the detection of a certain Ts_k to neck or low back pain presence or intensity. Thirdly, there was a lack of thermographic data of the back in literature to compare our data of healthy young adults. Future studies should evaluate the thermal profiles of the back of professional athletes, sport by sport, and its connection with the frequency and intensity of neck and back pain.

Conclusions

For the first time in literature, we evaluated the thermographic profile of healthy young adults practicing different sport disciplines comparing it with those of healthy sedentary people. We found that inactive individuals manifest a statistically significant higher temperature in the cervical, dorsal and lumbar area of the back. These thermographic data on healthy young adults could be useful for clinicians and sport trainers as a reference to compare their data with a healthy sportive and sedentary control.

Infrared Thermography for the Evaluation of Adolescent and Juvenile Idiopathic Scoliosis: A Systematic Review

Federico Roggio [1,2], Luca Petrigna [1], Veronica Filetti [1], Ermanno Vitale [3], Venerando Rapisarda [3], Giuseppe Musumeci [1,4]

[1] Department of Biomedical and Biotechnological Sciences, Human, Histology and Movement Science Section, University of Catania, Via S. Sofia n°87, 95123, Catania, Italy.
[2] Sport and Exercise Sciences Research Unit, Department of Psychology, Educational Science and Human Movement, University of Palermo, Via Giovanni Pascoli 6, Palermo, 90144, Italy
[3] Department of Clinical and Experimental Medicine, Occupational Medicine, University of Catania, Occupational Medicine; Via Santa Sofia n°78, 95123 Catania, Italy
[4] Research Center on Motor Activities (CRAM), University of Catania, Via S. Sofia n°97, 95123, Catania, Italy.

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1. Introduction

Adolescent and Juvenile Idiopathic Scoliosis (AJIS) are defined as a three-dimensional deformity of the spine with a multifactorial aetiology involving genetic, environmental, and lifestyle factors [286]. AJIS is characterized by a structural alteration of the spine's regions, presenting vertebrae rotated and translated in relation to normal body axes [287]. The Scoliosis Research Society (SRS) suggests the diagnosis of scoliosis when there is axial rotation and the curve exceeds the 10 ° Cobb angle. Several classifications of scoliosis have been proposed; however, the International Society for Orthopaedic and Rehabilitation Treatment of Scoliosis (SOSORT) recommends three main characteristics when approaching it: Age of diagnosis, Cobb degrees, and Apex of the scoliotic curve [288].

The clinical assessment of AJIS concerns the application of Adam's forward bending test, whose positivity is pathognomonic for scoliosis [289], and the Scoliometer, which measures scoliosis' hump appearing from Adam's test [290]. Radiography is the gold standard for identifying and monitoring scoliosis [291], even if it is associated with increasing awareness of the potential adverse effects of exposure to x-rays [291]. The Italian Scoliosis Society suggests a two projections x-ray at the first scoliosis assessment and a subsequent x-ray at least one year later [292]. Different non-invasive and radiation-free methods have been proposed to evaluate scoliosis without harmful effects. Such methods include Moiré topography [293], rasterstereography [29,294], 3D ultrasound imaging [248,295], 3D scanner [296], and infrared thermography (IRT) [297].

IRT is a non-invasive method that provides information on body thermal changes due to different conditions such as physical activity [203], metabolic alterations [205], rheumatic diseases [204], musculoskeletal disorders [298], as skin temperature change is an indicator of underlying processes [206]. Although this procedure generally depends on the environment and surrounding conditions, several reasons promote acceptance among the medical community. IRT is a non-contact and non-invasive method that provides quick measures in a couple of minutes. Clinicians can quickly understand the pathology they are observing thanks to the color pattern of the acquisition. Additionally, this method has no adverse effects and records the natural radiation coming from the skin's surface, resulting ideal for frequent use [299]. The interest in IRT applications to recognize back disorders is constantly growing as awkward posture causes altered muscle activity, which is responsive to thermal analysis. Lasanen et al. [300] employed IRT to discriminate muscle activity in working postures, Girasol et al. [301] found that patients with chronic neck pain present a reduction in skin temperature at trigger points of the trapezius. However, there is still controversy about how back pain responds to IRT, as Alfieri et al. [280] found that the temperature of the lumbar skin increased in patients with low back pain, while Roy et al. [302] found a reduction in the paraspinal cutaneous temperature in a similar population. Except for these controversial points, IRT is effective in assessing asymmetries in temperature distribution, appearing versatile in monitoring scoliosis throughout its course. Several aspects foster the applicability of IRT in the screening, diagnosis, and follow-up of scoliosis. It may result valid in the clinical setting when scoliosis is suspected, shifting further the radiographic examination, thus avoiding unnecessary x-rays exposure to adolescents. Improper posture caused by an altered scoliotic proprioceptive stimulus [303] and an asymmetric electromyography activity of the back muscles [304] are the main aspects supporting the validity of thermography in the evaluation of scoliosis. Paraspinal muscles of the convex side are characterized by a stronger RMS electromyography than those of the concave side [305]. Specifically, Kwok et al. [305] observed a muscle impairment in thoracic (one curve) and thoracolumbar (two curves) scoliosis, where the spine alteration affects the paraspinal muscle activity. Cooke et al. [297] in 1980 conducted one of the first thermography studies in idiopathic scoliosis. They observed that scoliosis is the most frequent cause of thermal asymmetry of the spine in adolescents and provided a high precision of the IRT for detecting scoliosis of the dorsal spine [297]. The leading assumption underlying the use of IRT in the evaluation of scoliosis is that in muscles analyzed by means of comparison, the temperature difference between the left and right sides of the back is minimal in subjects without scoliosis. On the contrary, scoliotic people show distinct differences in back muscle thermal activity, presenting an asymmetric temperature between the considered muscles.

This systematic review aims to analyze the applicability of IRT as a diagnostic method in scoliosis evaluation in discriminating thermal differences between the right and left sides of the back.

2. Materials and Methods

2.1 Search strategy

A systematic review of the literature was conducted on April 4, 2022, in PubMed, Web of Science, Scopus, and Google Scholar. Articles dealing with the use of IRT in AJIS management were selected according to the following string: (Infrared Camera OR Thermography OR Infrared Thermography OR Thermal Camera OR IRT OR Infrared Thermal Imaging) AND (Scoliosis OR Idiopathic Scoliosis OR Adolescent Idiopathic

Scoliosis). The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines were used [306]. The exclusion criteria were: articles regarding surgery, animals, low back pain and neck pain, radiculopathy, other spine pathologies, injuries, physical therapy treatments. Our systematic review fulfilled the criteria of the PICO tool:

- Population: children (age 3-9) or adolescents (age 10-17);
- Intervention: assessment of scoliosis with IRT;
- Comparison: IRT compared to x-rays or scoliometer;
- Outcome: discrimination of temperature asymmetry of back the back in scoliotic patients.

2.2 Selection Process

The articles were stored in EndNote 20 (EndNote 20 desktop version, Clarivate, Philadelphia, PA) [307] and duplicate papers were selected and automatically removed. The screening process and analysis were performed separately by two independent investigators. The principal investigator resolved disagreements in the selection process. The articles were first screened by title and abstract. Only articles reporting the use of IRT to evaluate scoliosis were selected for screening, considering any clinical reports, regardless of the level of evidence, published after 1990. The references of each selected article were checked to find more articles of interest. Second, the full text of the selected articles was screened, with further exclusion when no scoliosis assessment method was adopted.

2.3 Data collection

The full text of all the articles selected was read to identify meaningful information. Relevant data extracted from selected studies are: the number of patients, sample classification, age range, scoliosis evaluation protocol, type of IRT used, IRT method applied, IRT results, and conclusions.

2.4 Risk of bias and applicability assessment

The Quality Assessment of Diagnostic Accuracy Studies-2 (QUADAS-2) tool [308] was employed to assess the risk of bias, applicability, and diagnostic accuracy of IRT in the treatment of scoliosis. It consists of four key domains: patient selection, index test, reference standard, flow, and timing. The first three domains assess both the risk of bias and applicability; flow and timing domain assesses only the risk of bias. Each domain was rated as high, low, or unclear risk of bias. Each study was evaluated for all domains, providing a single general score for all studies included in this systematic review.

3. Results

Of the 587 articles screened, only 10 were examined in their full text. A number of 4 articles were excluded due to the inconsistency of the applied method; one article was excluded because the article was written in Korean and the results were not provided; only 5 articles were found to be eligible for inclusion in the present systematic review. The screening process is presented in Figure 1. All articles used IRT to detect differences in the temperature distribution of paraspinal muscles, and one article aimed to generate a machine learning model to classify thermographic scoliosis. Three articles compared the IRT measures with x-rays and only included Cobb's angle assessment. The study includes 646 participants, 449 of them with scoliosis. The age range was 9-17, 66 were male, 146 were female, and of 434 the gender was not specified. The study characteristics are summarized in Table 1.

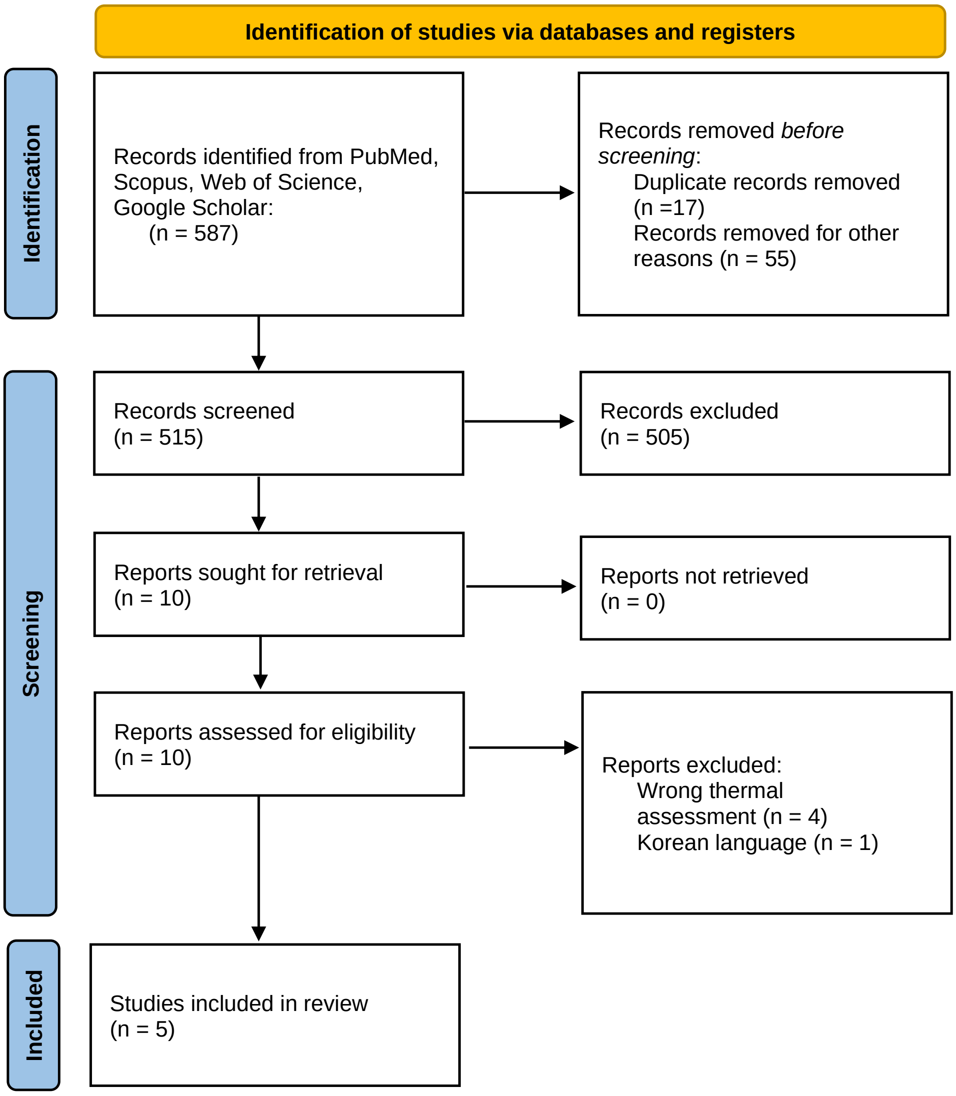

***Figure 1**. PRISMA flow diagram for new systematic reviews which included searches of databases and registers only*

Table 1. Characteristics of the studies

Author, Year	Sample (M/F)	Classification	Mean age	Scoliosis evaluation	IRT system	IRT assesment	IRT results	Conclusions
Dragan et al. (2002) [309]	403	1st, 2nd, and 3rd Gruca's curvature degree (GCD)	9-17	RX	NA	Thermal difference between the convex and concave side of the spine	Mean temperature difference: 1st GCD= 0.83°, 2nd GCD= 1°, 3rd GCD= 1.34°, CG= 0.31°	The greater the deformation between the concave and convex sides, the greater the thermal difference between the two parts of the back.
Dyszkiewicz et al. (2007) [310]	30/60	A1 – thoracic scoliosis A2 – thoracolumbar, primary arc lumbosacral A3 – thoracolumbar scoliosis mirror-like B – control group	10-15	RX	Agema 450	Thermal differences of the left and right paravertebral muscles	A1= 0.921 ± 0.085 A2= 0,87 ± 0.08 A3= 0.78 ± 0.09 B=0.94 ± 0.11	The highest correlation of muscle activity asymmetry was present only in group A3. Groups A1 and A2 did not present it, probably due to a reached osseous stabilization.
Kwok et al. (2017) [230]	31	Scoliotic = spine curve >10° Non-scoliotic = no spinal curve	10-13	Scoliometer and scoliosis ultrasound scan	FLIR E33	Thermal differences of the left and right Trapezius, Latissimus Dorsi, and Quadratus Lumborum muscles	Mean temperature difference: T= -0.077 ± 0.149, LD= -0.275 ± 0.203, QL= -0.300 ± 0.436	Scoliotic subjects demonstrate a statistically significant difference between the left and right sides of the regions of interest due to the higher IR emission of the convex side of the observed area.
Ka Natalie et al. (2021) [311]	18/64	Group 0 < 20°, Group 1 20°-	10-13	RX	FLIR E33	Thermal matrix of the back surface of a patient	With an accuracy > 0.80 the machine learning	With an accuracy > 0.80 the machine learning approaches

		30°, Group 2 31°- 40°, Group 3 > 40°					approaches show promising potential for the use of thermography to predict the severity of scoliosis.	show promising potential for the use of thermography to predict the severity of scoliosis.
Lubkowska and Gajewska (2020) [312]	18/22	Scoliotic = spine curve >10° Non-scoliotic = no spinal curve	8-12	Adam test and scoliometer	FLIR T1030sc	Thermal differences of left and right: upper back, lower back, abdominal, frontal thigh, back thigh, frontal shank, back shank	Mean temperature difference: UB= 0.4 ± 0.1, LB= 0.2 ± 0.2, Ch= 0.1 ± 0.1, Ab= 0.1 ± 0.1, FT= 0.4 ± 0.1, BT= 0.3 ± 0.1, FS= 0.2 ± 0.1, BS= 0.5 ± 0.2	Scoliotic children present thermal asymmetry of the upper back, thigh, and back shank with a high positive correlation between spinal rotation angle and thermal asymmetry.

CG: control group, GCD: gruca's curvature degree T: trapezius, LD: latissimus dorsi, QL: quadratus lumborum, UB: upper back, LB: lower back, Ch: chest, Ab: abdominal, TF: frontal thigh, TB: back thigh, SF: front shank, SB: back shank

3.1 Risk of bias and applicability assessment

The QUADAS-2 tool provided a valuable method for analyzing IRT's risk of bias and applicability in scoliosis evaluation. One study showed good quality by scoring 6 low risks in the seven key domains; two studies showed average quality by scoring 5 low risks in the seven key domains. The remaining studies did not provide sufficient information to claim good quality. All scores are reported in Table 2. Second, we analyzed the general quality of all the articles included in this systematic review.

Regarding the risk of bias (Figure 2A), index test and reference standard are the domains achieving the higher risk of bias. Three studies have a high risk of bias in the index test domain because they already classified patients before performing IRT. Two studies have a high risk of bias for the reference standard domain because they used clinic tests that may be passible for subjectivity. In terms of concerns regarding the applicability (Figure 2B), two studies showed high concerns regarding the IRT applicability, while two studies did not use the x-rays as a reference test.

Table 2. Tabular presentation of QUADAS-2 study assessment

Study	**Risk of bias**				**Applicability concerns**		
	Patient selection	*Index test*	*Reference Standard*	*Flow and Timing*	*Patient selection*	*Index test*	*Reference standard*
Dragan et al. (2002) [309]	↑	↑	↓	//	↑	//	↓
Dyszkiewicz et al. (2007) [310]	↓	↑	↓	↓	↓	↓	↓
Kwok et al. (2017) [230]	↓	↓	↑	↓	↓	↓	↑
Ka Natalie et al. (2021) [311]	↑	↑	↓	//	↑	↓	↓
Lubkowska and Gajewska (2020) [312]	↓	↓	↑	↓	↓	↓	↑

↑ = high risk, ↓ = low risk, //= unclear risk

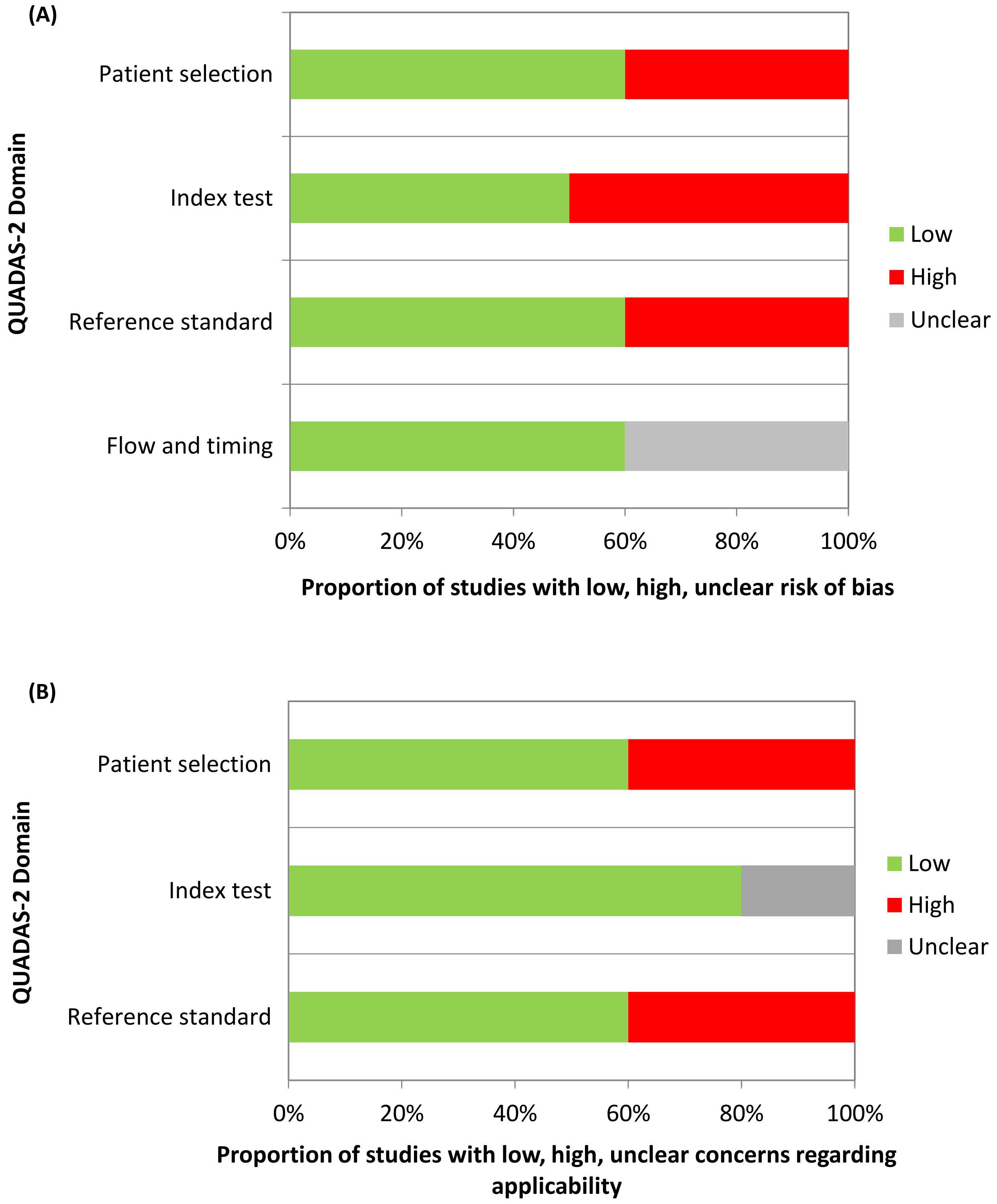

Figure 2. *Graphical representation of the QUADAS-2 results. (A) Risk of bias assessment; (B) concerns about applicability.*

3.2 Scoliosis evaluation

The comprises of papers differ in the classification of the scoliosis of patients. Three articles classified as scoliotic patients those showing a spine curve > 10°, and the three articles evaluated scoliosis with the Adam test and the scoliometer. Dragan et al. [309] followed Gruca's classification of scoliosis (1^{st} grade = spine curve < 30°; 2^{nd} grade = spine curve 30°- 60°; 3^{rd} grade= spine curve 60°- 90°), and analyzed scoliosis using x-rays. Dyszkiewicz et al. [310] analyzed the x-rays and divided the scoliotic group based on the scoliosis situs, i.e. mirror-like thoracic, thoracolumbar, thoracolumbar. Additionally, Ka Natalie et al. [311] analyzed the x-rays to classify the patients; however, they used a personal classification that divided the patients into: group 0 = scoliosis < 20°, group 1 = scoliosis 20°- 30°, group 2 = scoliosis 31°- 40°, Group 3 > 40°.

3.3 Infrared thermography assessment

All studies used IRT to evaluate the thermal average difference between the convex and concave paravertebral muscles. Specifically, Lubkowska et al. [312] analyzed the back muscles and also the abdominal, front, and back thigh, front, and back shank. The IRT results were expressed differently by the authors. Two studies stratified the mean temperature difference (MTD) by scoliosis classification, while the other studies classified MTD according to muscle selection. Dragan et al. [309] found a thermal difference between the convex and concave sides of MTD= 0.83 in the group with a spinal curve < 30°, MTD= 1 in the group with a spinal curve of 30°-60°, and MTD= 1.34 in the group with a spinal curve of 60 °-90 °. Their findings suggest that the thermal difference between the convex and concave sides increases with increasing deformation between the sides. Dyszkiewicz et al. [310] found a thermal difference of paravertebral muscles of MTD= 0.921 ± 0.085 in the group with thoracic scoliosis, MTD= 0,87 ± 0.08 in the group with thoracolumbar scoliosis, and MTD= 0.78 ± 0.09 in the group with thoracolumbar scoliosis mirror-like. The authors did not provide any tests to confirm the significance of the results; furthermore, they conclude by highlighting a correlation between muscle activity asymmetry and IRT only in the thoracolumbar scoliosis mirror-like group. Kwok et al. [230] found a statistical difference in the three muscles considered by setting a temperature cut-off of 0.3 ° C. The left and right trapezius showed an MTD = -0.077 ± 0.149 (p= 0.048), the latissimus dorsi showed an MTD = -0.275 ± 0.203 (p= 0.000), and the quadratus lumborum MTD= -0.300 ± 0.436 (p=0.002). These results demonstrate a thermal difference in the muscles considered between the convex and concave sides of the back. Lubkowska et al. [312] found a statistical difference only in the upper back, MTD= 0.4 ± 0.1 ($p < 0.001$), frontal thigh, MTD= 0.4 ± 0.1 ($p < 0.01$), back thigh, MTD= 0.3 ± 0.1 ($p < 0.001$), and back shank, MTD= 0.5 ± 0.2 ($p < 0.001$). Furthermore, they demonstrated a high correlation between thermal asymmetry and spine rotation angle. Ka Natalie et al. [311] analyzed the IRT measures and x-rays with several machine learning approaches. Their results pointed to an accuracy > 0.80 in predicting the severity of scoliosis through IRT.

4. Discussion

All the collected articles highlight the effectiveness of IRT in discriminating the thermal changes of scoliosis between the right and left sides of the back. The application of IRT has progressed during the last 30 years in instrument quality, software analysis, measurement techniques, and clinical protocols. These advances enhanced the understanding of human body temperature changes, determining more evidence for the diagnostic accuracy of IRT in different disorders [313]. Specifically, precise standardization is essential because different protocols can alter the results interpretation, the image processing, or the repeatability of the region of interest selection [313]. Furthermore, this does not allow the comparison of the data between studies, making impossible the creation of a normative data set [314].

The evaluation of scoliosis can be challenging due to the specific need to demonstrate the presence of rotation of the vertebrae that distinguishes it from a posture alteration that occurs without morphological changes in the spine. Actually, neither IRT can precisely diagnose changes in scoliosis, but it can be a versatile and reliable tool to detect presumable changes in the spine and then guide clinicians to specific exams only when needed. Fong et al. [315] collected all articles on school scoliosis screening to debate the efficacy of non-invasive methods in the preventive evaluation of scoliosis. Of the 36 studies included in the meta-analysis, 23 used only the forward bending test, eight also measured the angle of rotation of the trunk, and two included Moiré topography. They found a general heterogeneity between studies, and the main finding is that the forward bending test alone is insufficient for the school scoliosis screening. School screening programs are necessary because they can detect scoliosis early, mostly when morphological changes are not yet visible: A preventive approach can determine a less invasive method when diagnosed early [316]. A study conducted in an Italian school showed a high incidence of back disorders, mainly scoliosis, performed only with clinical tests [236]. This kind of study fosters the need for a valid method to assess these disorders, such as IRT.

The articles considered in this systematic review provided exciting findings on the evaluation of scoliosis through IRT. Only Dyszkiewicz et al. [310] showed a high quality because the authors correctly addressed all measures according to the gold standard, the classification of scoliosis, and the IRT results. Their results proved the validity of IRT only for mirror-like thoracolumbar scoliosis and not for thoracic and lumbosacral. Furthermore, the study was conducted in 2007, so the IRT measures and the respective software may be outdated compared to modern systems. The results provided by Kwok et al. [230] and Lubkowska et al. [312] are similar; they both found a significant difference between the left and right muscles of the upper back and the lower back with a mean difference of ± 0.4°. Even if Kwok et al. [230] did not employ the x-rays exam, they provided a valuable approach by screening the children firstly with the forward bending test and scoliometer. Then only those with trunk rotation > 10° were evaluated with a spine ultrasound system, adding IRT detection. While they firstly screened the children and then used the IRT, Lubkowska et al. [312] recruited all the patients and conducted the scoliosis evaluation with the forward bending test, scoliometer, and IRT as a whole single exam. This method likely appears to be the most suitable; however, since the IRT has not yet demonstrated its maximum reliability in assessing scoliosis, it is recommended to compare the results with the gold standard, i.e., x-rays. The findings of Dragan et al. [309] support the validity of IRT in this field; however, they classified patients with an unconventional scale, Gruca's curvature degree, and provided results with a substantial difference between the convex and concave sides of scoliosis. We believe that their results must be interpreted with caution due to the considerable difference from the other papers included in this systematic review. Finally, we included the study of Ka Natalie et al. [311] because even if their results did not discuss the validity of IRT for scoliosis evaluation, they employed its use within machine learning methods. The main finding is that their model scored an accuracy > 0.80, showing encouraging potential to predict the severity of scoliosis. Machine learning in medicine is quickly spreading because it can facilitate clinicians to anticipate the future events of a disease, drawing valid conclusions far beyond the skills of clinicians [317]. Out of the studies analyzed, we also considered the study by Vutan et al. [318] using IRT to analyze muscle activation during exercises in patients with scoliosis, showing that IRT can detect asymmetric activation of the back muscles during exercises.

The main finding of this study highlights the IRT application to evaluate the thermal asymmetry of scoliosis by discriminating the abnormal thermal pattern of the back. However, the comprised articles reveal the absence of a collectively agreed methodology to assess scoliosis with IRT. We support the research approach of Kwok et al. [230] since they affirmed that the convex side of scoliosis presents an increased temperature than the concave side, currently representing a milestone of the application of IRT in the diagnosis of scoliosis. Nevertheless, their study should be repeated employing the x-rays as reference standard.

Although different authors have already provided detailed guidelines for the applicability of IRT for clinical thermal images [243] and sports sciences [241], we observed the absence of specific recommendations through this systematic review for the collection of thermal images in scoliotic patients. Standardized acquisition can reduce systematic errors and increase the quality of acquisition [314,319]. In addition to established protocols for the environment and camera or subject positioning, we suggest several recommendations when analyzing scoliosis. For the exam procedure, forward bending test and scoliometer, can increase the classification accuracy; furthermore, by marking the spine reference point, the selection of the region of interest can be located more accurately. It is essential to divide the sample into specific classes for age, Cobb degrees, and apex of the vertebrae of scoliosis, strictly following the SOSORT classification of scoliosis [288]. Finally, it is mandatory to adequately report the results highlighting which side of the scoliosis presents the higher temperature. We raise this issue as the included articles of this systematic review used different classifications, which caused the inability to compare the results correctly. Although the findings provided interesting results for IRT application with scoliosis, further studies should compare thermal acquisition with current methods.

Table 3. Specific recommendations for the evaluation of scoliosis with infrared thermography

Exam procedure	Perform the forward bending test and measure the trunk rotation with a scoliometer. Then, mark with a skin pencil the spine reference points: C7, Thoracic apex, T12, L3 and S2.
Scoliosis classification	*Chronological* – age (juvenile: 3–9, adolescent: 10–17, adult: 18+) *Angular* – Cobb degrees (low: < 20°, moderate: 21°–35°, moderate to severe: 36°–40°, severe: 41°–50°, severe to very severe: 51°–55°, very severe: 56°+) *Topographic* – apex (cervical: C1–C7, cervico-thoracic: C7–T1, thoracic: T1-2 disc-T11–12 disc, thoraco-lumbar: T12–L1, Lumbar: L1-2 disc)
Region of interest	Compare the thermal differences of left and right trapezius, latissimus dorsi, and quadratus lumborum.
Results presentation	Describe the thermal difference between the regions of interest and highlight the thermal asymmetry of the convex and concave sides of scoliosis.

Due to the lack of standard criteria for IRT classification of scoliotic patients, currently we suggest comparing the results with x-rays to make exact measurements. If researchers follow these recommendations, we expect to increase the IRT accuracy massively, avoid as much as possible exposition to x-rays, and provide sufficient data to allow machine learning methods to recognize scoliosis just by thermal acquisitions. Future studies should investigate the correlation between cobb angles and thermal differences to establish a plausible dependence of muscular thermal response to spinal alterations. Then, IRT could be compared or associated with existing non-invasive methods to enhance the analysis of musculoskeletal alterations.

5. Conclusions

This systematic review showed the applicability of IRT to diagnose scoliosis by measuring the thermal activity of the back muscles. The results support the effectiveness of this method in pointing out the temperature asymmetry between the right and left sides of the back. Although exhaustive guidelines support its applicability in human body analysis, we proposed few recommendations to enhance its strength in the evaluation of scoliosis in order to provide precise results and thus guide research toward the complete validity of this method. Future studies should clearly define the correlation with the gold standard for scoliosis diagnosis and further investigate the applicability with the non-invasive methods that already exist.

Kinesiological Treatment of Early Spine Osteoarthritis in a Motorcyclist

Federico Roggio [1,2], Bruno Trovato [1], Caterina Ledda [3], Venerando Rapisarda [3] and Giuseppe Musumeci [1,4,5]

[1] Department of Biomedical and Biotechnological Sciences, Human, Histology and Movement Science Section, University of Catania, Via S. Sofia n°87, 95123, Catania, Italy.
[2] Sport and Exercise Sciences Research Unit, Department of Psychology, Educational Science and Human Movement, University of Palermo, Via Giovanni Pascoli 6, Palermo, 90144, Italy
[3] Department of Clinical and Experimental Medicine, Occupational Medicine, University of Catania, Occupational Medicine; Via Santa Sofia n°78, 95123 Catania, Italy
[4] Research Center on Motor Activities (CRAM), University of Catania, Via S. Sofia n°97, 95123, Catania, Italy.

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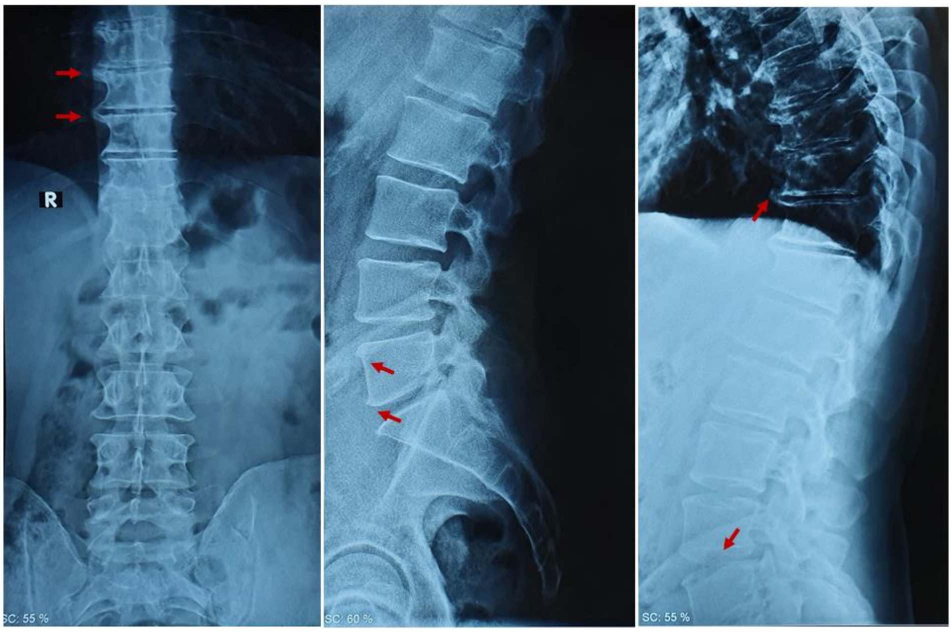
1. Introduction

Spine osteoarthritis (OA) is widespread, with estimations of its prevalence ranging from 40 to 85% of the entire world population [320]. OA is rarely linked to spinal disease because in the majority of cases, this disease is linked to the peripheral joints (hands and knees) rather than to the spine. The macroscopic evidence reveals disc space narrowing and vertebral osteophyte formation [321]. Although a definite correlation between spine OA and low back pain (LPB) has not been found, several conditions may predispose the spine to degenerate into an osteoarthritic condition. The common causes of low back pain are internal disc disruption, facet joint arthrosis, and sacroiliac joint arthrosis [322], while OA is a disorder of the synovial joints. Both conditions can affect facet and sacroiliac joint arthrosis, causing LBP deriving from OA joint degeneration [323]. As stated by Laplante et al. [323], OA is not the main cause of all spinal joint problems; however, the relative percentage of joint pain due to OA is age-related. LBP is a chronic condition, with nearly 80% of the population undergoing at least one event of LBP in their lifetime [324]. The complicated connection between spine radiographs and LBP has many clinical and research challenges. In individuals with cancer, LBP may stem from conditions that are challenging to identify with radiographs, such as malignant spinal cord compression, which can cause pain, paresthesia, and motor weakness [325]. High-amplitude, low-frequency vibration has been recognized as a risk factor for back pain, intervertebral, and temporomandibular disc degeneration [326-328]. Although whole-body vibrations (WBV) have been reported as a valuable treatment for back pain and osteoporosis, other studies suggest that the WBV effects on bones may vary with age, genetics, anatomical location, and application [329].

Off-road motorcycling is a hazardous sport with little known about its connection to spine lesions compared to other well-known sports [330]. Off-road motorcyclists are constantly exposed to WBV, which may predispose the body to excessive stress on the musculoskeletal system. The most notorious causes of spinal damage are impact, motorcycle jumping, or the loss of control from high-speed sway [331]. Some lesions, such as vertebral fractures leading to paralysis, permanent handicap, and lethal injuries, have been described in connection with motocross accidents [332]. In this case report, we observed the presence of spine OA in an enduro motorcyclist and how a kinesiological approach determined joint mobility recovery and pain reduction. Recent interest in using exercise therapy and Kinesio taping application showed improvements in treating chronic OA and LBP [163,333]. This case report aims to provide the first documented evidence of early spine osteoarthritis in enduro motorcycle overuse and the long-term management effects of a non-invasive kinesiological approach to reduce pain and inflammation and improve spine mobility and muscle strength.

2. Case Report

A 45-year-old off-road motorcyclist—1.78 cm tall, with a weight of 80 kg—experienced acute pain over the thoracolumbar region during a vintage motorcycle race championship in the absence of any accident or critical event to explain the acute pain onset. The patient was clinically evaluated after the race and then forced to suspend the championship due to this condition. Due to the acute pain, an X-ray exam was prescribed. The radiologist's diagnosis showed the absence of traumatic bone injuries but revealed discrete signs of diffuse osteoarthritis with dorsal interbody bony bridges, moderate osteophytes, and narrowing of disc spaces from T12-L1 and L5-S1; a clinical condition similar to that of an elderly osteoarthritic spine [334], classified as grade 2 on the K&L scale [335], as shown in Figure 1.



(a) **(b)** **(c)**

Figure 1. *Radiographic examination of the spine: (**a**) represents the coronal plane, and the red arrows indicate the osteoarthritic degeneration at the right side of the vertebrae; (**b**) represents the sagittal plane of the lumbar region, and the red arrows indicate the presence of osteophytes at L5; (**c**) represents the sagittal plane of the thoracic and lumbar region, and the red arrows indicate the osteoarthritic degeneration of both segments.*

The patient, Figure 2, began his motocross career 28 years ago with training approximately two times a week for the entire year. The patient is a labor consultant, an occupation that does not require excessive manual effort. As reported by the patient, the symptoms (inability to fully extend and flex the spine, pain during spine extension and flexion, loss of strength, and difficulty accomplishing natural movements) began mildly one week before the race and reached their peak during the race. The patient reported episodes of low back pain in the previous year but no acute events during that time. The patient's clinical history of motocross-related injuries included various injuries, such as trauma to the sacral bone eight years prior to the study, a left knee tibial plateau fracture five years prior to the study, and varicose vein surgery in both lower limbs three years prior to the study. The patient's clinical and family history bore no trace of osteoarthritis, rheumatoid arthritis or microfractures in the spine.

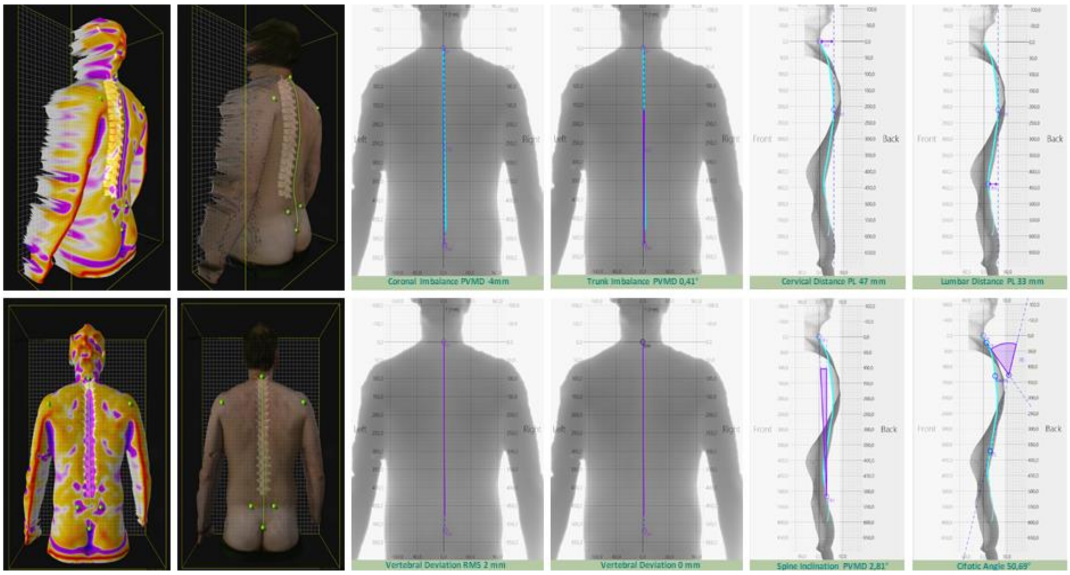
Figure 2. *The forty-five-year-old motorcyclist during a race.*

2.1. Clinical Examination

This study was approved by the local ethics committee of the Research Center on Motor Activities (CRAM) (Protocol n.: CRAM-017-2020, 16 March 2020) and the University of Catania, in accordance with the Declaration of Helsinki. Informed consent was obtained from the patient. For the clinical evaluation, the following approaches were utilized to collect the data that are most relevant to the case: the Spine 3D (Sensor Medica®, Rimini, Italy) was used to evaluate the spinal deformities, if present, through infrared rays. The system generates a 3D model of the spine by calculating specific deformities. It assesses the presence of scoliosis, pelvic obliquity, thoracic kyphosis, lordosis angles, and lateral deviations. BioFet (Fisiotools, Roma, Italy) is a portable electronic dynamometer employed to evaluate the muscle force in the extensor spine muscles. Bobomotion (Fisiotools, Roma, Italy) is a miniature sensor able to analyze a range of motion. Specifically, it has been used to evaluate spine motion in flexion, extension, and inclination. Taping Elastico® (ATS, Arezzo, Italy) is Kinesio taping applied to reduce pain and increase mobility. Muscle force, range of motion, and the Visual Analogue Scale (VAS) score were collected at the beginning of each week for four weeks and then at 3–6 month follow-up intervals.

2.2. *Physical examination*

The patient was lying on the examination table in prone decubitus to evaluate the metameric movement of the lumbar spine [336]. The presence of Maigne's syndrome [337], i.e., thoracolumbar junction syndrome, was evaluated to discriminate the presence of thoracolumbar joint inflammation and radicular pain. The spinal extension force was evaluated through the dynamometer use. Lying in prone decubitus with his arms by his sides, the patient was required to extend his spine while the clinician exerted posterior resistance through the dynamometer. The spine motion was evaluated with the patient in a sitting position on the examination table with legs not resting on the ground and arms crossed resting on opposite shoulders. The patient was required to perform a lateral inclination to the left and right and then a flexion and extension. A miniature sensor attached to an elastic belt was placed on the chest to evaluate the spine's range of motion. The spine rasterstereography elaborated the spine's morphometric analysis to discriminate the presence of scoliosis and the increase or the reduction in the spine's curves. The patient was required to stand in the upright position for 5 s with the back and the buttocks uncovered to ensure a valid measurement because the pants' pressure on the buttocks could cause a surface alteration in the back [338]. During the clinical spine examination, the range of motion (ROM) was, respectively: 10° inflection and 5° in extension, 10° in right inclination, and 17° in left inclination. The patient showed signs of mechanical and functional blocks with a range of motion reduction, specifically at the T12-L1 junction and L4-S1 junction, with no radicular pain present. The VAS score was assessed at a value of 8. The spinal extension muscle force was evaluated through the digital dynamometer. The maximal average force exerted was 3.19 kg, and at 1.2 s, muscle contraction sharply stopped. A morphometric spine analysis (Figure 3) was carried out for further investigation. The morphometric spine analysis was conducted to analyze the physio anatomy of the back in its entirety. There were no lateral deviations in the coronal plane and no alterations in the sagittal plane, except for a slight reduction in cervical and lumbar depth. These conditions cannot justify the presence of early spine osteoarthritis.



(**a**) (**b**) (**c**) (**d**)

Figure 3. *Spine rasterstereography accomplished through the Spine3D system. (**a**) represents the 3D reconstruction of back concavities. (**b**) represents the spine reconstruction over the patient's spine photo. (**c**) represents the coronal plane measurements. (**d**) represents the sagittal plane measurements.*

2.3. Therapeutic Intervention

For the first week, the physician prescribed rest and NSAID anti-inflammatory therapy as needed to reduce pain and inflammation, according to the clinical guidelines for managing non-specific low back pain **[339]**. The physician observed that the functional limitation derived from the osteoarthritic degenerations through radiographic examination of the spine. Then, by the second week, in agreement with the kinesiologist, a non-invasive kinesiological treatment based on antalgic therapy with Kinesio taping application was administered without NSAID anti-inflammatory therapy. The Kinesio taping application was administered twice per week, while the antalgic therapy for gymnasts required administration at home 3 times per week.

2.4. Kinesio taping application

Three Kinesio tapes were applied to the patient's back to reduce pain perception and increase mobility. The tapes were "Y-strips" with a length of approximately 35 cm, an anchor of 8 cm on the buttocks, and applied over the spine up to T10 vertebrae. For the application, the patient was standing in an upright position while the anchor of the blue tapes was placed on the sacrum and the pink tapes on the gluteus maximus. Subsequently, forward bending of the trunk was executed while the two tails of the tapes were applied without stretching because of their stabilizing effect. The blue tails were applied in the direction of the paravertebral chains, and the pink tails were applied in the direction of the latissimus dorsi and sacrospinalis group of muscles, as shown in Figure 4.

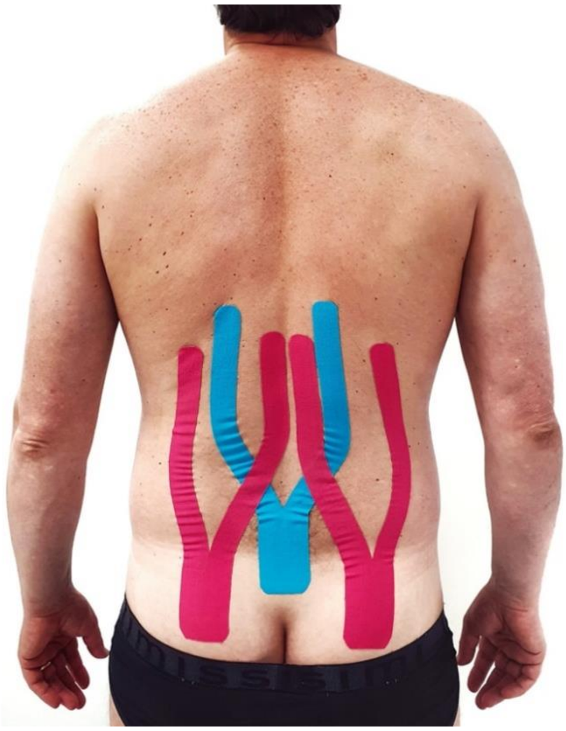


Figure 4. *Kinesio taping application in a Y shape. The blue tape is applied over paravertebral chains and the pink tape over the latissimus dorsi and sacrospinalis group of muscles.*

2.5. Exercise administration

The following exercises, provided by the ISICO (Italian Spine Scientific Institute) online platform [340,341], were administered to relieve the spine pain and increase mobility (Figure 5). We selected exercises concerning spine mobilization and pain relief, as a number of authors confirmed the high validity of exercise administration in LBP treatment [342-344]. During week two, the exercises focused on pain reduction:

1. Upright position with the back leaning against a wall. Bend the knees and push the back against the wall while exhaling (Figure 5a);
2. Sitting position with the back against a wall. Place a rolled-up cloth under the lower back and exert rhythmic pressure while exhaling (Figure 5b);
3. Supine position. Breathe while inflating the belly and chest alternately. With each exhale, press the lower back to the ground (Figure 5c);
4. Supine position. Place a rolled-up cloth in the lumbar area and exert rhythmic pressure while exhaling (Figure 5d);
5. Supine position. Place a cloth under the painful part of the dorsal column and extend the arms while exhaling (Figure 5e);
6. Supine position. Place a cloth in correspondence under the painful area and carry out torsion movements of the trunk while exhaling (Figure 5f);
7. Supine position with legs flexed. Cross roll left and right with hands at the nape of the neck (Figure 5g);
8. Supine position. Flexion of the hips and pull the knees to the chest. Gently swing the trunk left and right (Figure 5h).

By week three, exercises 6, 7, and 8 were replaced with mobility exercises as follows:

9. Sitting position. Lateral trunk translation in kyphosis with arm extended laterally (Figure 5i);
10. Sitting position with a stick in the hands held high over the head. The lateral inclination of the trunk (Figure 5l);
11. Upright position placed beside a wall with the hand resting and the arm outstretched. With the other hand, push the pelvis towards the wall (Figure 5m).

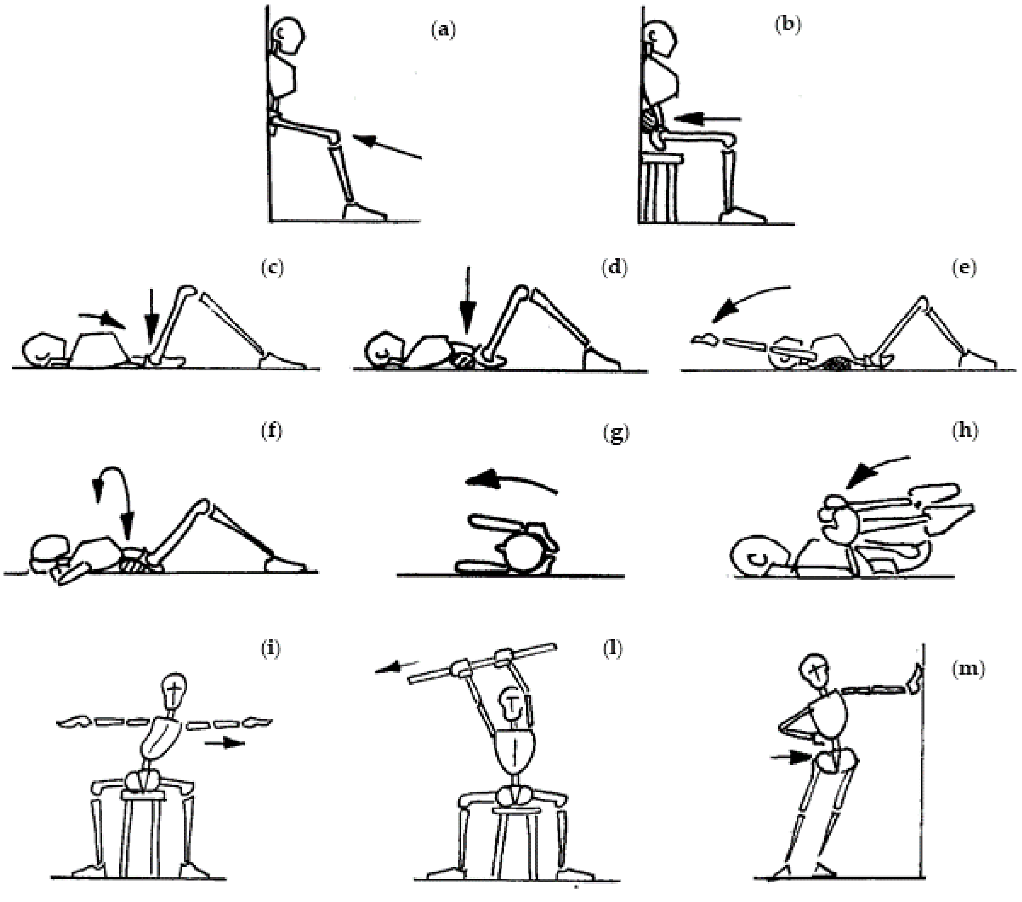


Figure 5. Visual explanation of home-based exercises. Exercises (a) and (b) aimed to increase the spine's stability. Exercises (c–h) aimed to reduce pain perception. Exercises (i–m) aimed to increase spine mobility.

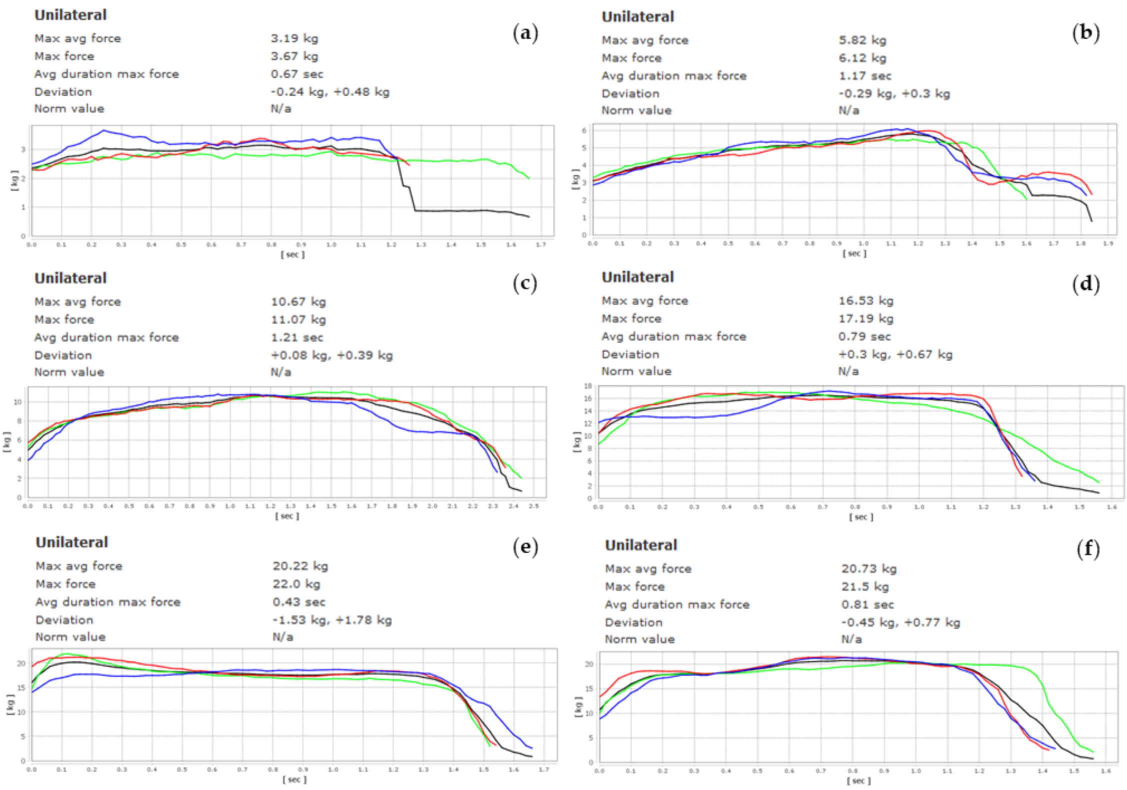
2.6. Changes in Therapeutic Intervention

The patient reported only transitorily pain relief during week two—the VAS score was 6—and a minimal improvement in the ROM. Based on the clinical outcomes, it was decided to repeat the treatment for a third week, finding a positive improvement in the ROM and a temporary improvement of pain: the VAS score was 4. Moreover, there was no contraindication for repeating the treatment relating to the patient's general health. Therefore, the treatment was administrated for the fourth week as well. In the last treatment, the patient reported a considerable amount of pain reduction, as confirmed by a VAS score of 2 and a positive improvement in the ROM. Throughout the entire treatment, the patient refrained from driving. In the third and sixth months, the patient repeated the same kinesiological treatment for three weeks without NSAID anti-inflammatory therapy, obtaining positive results in ROM improvement and pain reduction: the VAS score was 1. Spine ROM, VAS, and muscle force (Figure 6) were evaluated each week, as reported in Table 1.

Table 1. Physical evaluation of pain, mobility, and force through the weeks.

	Week 1	Week 2	Week 3	Week 4	3rd month	6th month
VAS scale	8	6	4	2	1	1
ROM flexion	10°	22°	35°	68°	75°	78°
ROM extension	2°	2°	8°	9°	15°	18°
ROM lateral inclination left	17°	20°	36°	55°	63°	67°
ROM lateral inclination right	10°	15°	27°	46°	58°	60°
Muscle force (kg)	3.19	5.82	10.67	16.53	20.22	20.73

VAS, visual analogue scale; ROM, range of motion °.



(a)

```
Unilateral
Max avg force            3.19 kg
Max force                3.67 kg
Avg duration max force   0.67 sec
Deviation                -0.24 kg, +0.48 kg
Norm value               N/a
```

(b)

```
Unilateral
Max avg force            5.82 kg
Max force                6.12 kg
Avg duration max force   1.17 sec
Deviation                -0.29 kg, +0.3 kg
Norm value               N/a
```

(c)

```
Unilateral
Max avg force            10.67 kg
Max force                11.07 kg
Avg duration max force   1.21 sec
Deviation                +0.08 kg, +0.39 kg
Norm value               N/a
```

(d)

```
Unilateral
Max avg force            16.53 kg
Max force                17.19 kg
Avg duration max force   0.79 sec
Deviation                +0.3 kg, +0.67 kg
Norm value               N/a
```

(e)

```
Unilateral
Max avg force            20.22 kg
Max force                22.0 kg
Avg duration max force   0.43 sec
Deviation                -1.53 kg, +1.78 kg
Norm value               N/a
```

(f)

```
Unilateral
Max avg force            20.73 kg
Max force                21.5 kg
Avg duration max force   0.81 sec
Deviation                -0.45 kg, +0.77 kg
Norm value               N/a
```

*Figure 6. Dynamometer muscle force graph through the weeks: (**a**) week 1, (**b**) week 2, (**c**) week 3, (**d**) week 4, (**e**) 3-month follow-up, (**f**) 6-month follow-up.*

3. Discussion

The prevalence of symptomatic spine osteoarthritis in individuals under 50 years of age is very uncommon and challenging to treat [345]. Considering the current literature [346-350] supporting the relationship between vibration and osteoarthritis, our perspective is that over time, the continuous vibrations caused by off-road motorcycle racing can create microtraumas that can lead to spine osteoarthritis. Furthermore, various authors [351-353] have analyzed the possible relationship between the WBV experienced by motorcyclists as one of the highest risk factors for low back disorders. For example, as Chen et al. [351] reported, the correct posture while riding is to maintain an upright trunk, as a forward bend in the trunk may predispose motorcyclists to adverse health effects while subjected to WBV. The most frequently injured regions are the extremities (upper and lower limbs) rather than the spine itself [331]. The subject of this study did not report any injury to other body regions aside from the spine. A possible explanation may be the difference in loading between the different spine segments related to driving functions and sitting, especially in stressful conditions such as training and competition. We hypothesize a possible connection between early spine OA diagnosis and the jolting stimulus caused by a motorcycle and rugged terrain for a prolonged period of time. Certainly, early spine OA cannot be univocally attributed to the vibrations caused by enduro off-road sports. However, as highlighted by Tian et al. [354], who investigated the prevalence of degenerative lumbar OA in 3859 Chinese adults, vibrations are reported as one of the higher risk factors associated with spine osteoarthritis among adults (OR: 2.21, 95% CI: 1.51–3.23; $p < 0.05$). These results strengthen the hypothesis that exposure to prolonged vibrations from enduro off-road sports may be deleterious to the spine, especially in this case report where the subject has practiced motorcycling for 28 years and continues to train twice a week. A detailed assumption provided by Patterson et al. [355] points out the possible connection to spine OA indirectly linked to an altered neuromuscular component. WBV could cause muscle inflammation, microtrauma, and nociceptive input to the spinal cord, conditioning the spine biodynamic response under vibrations. Secondly, in silico stress analysis of the lumbar spine, vibrations exposed cancellous bone and the cartilaginous endplate to tissue damage [356]. Vibration treatment applied over musculoskeletal structures could effectively reduce the unfavorable effects of aging on bone, cartilage, muscles, and tendons. However, the vibration parameters, i.e., amplitude, frequency, and magnitude of the oscillations, should be chosen based on the therapeutic need; otherwise, this treatment would have no effect or harmful effects [349,357]. Off-road motorcycling is considered a well-known sport, and because prevention is better than cure, the best support for these athletes could be the implementation of clinical joint examination in the limbs and spine instead of focusing primarily on the cardiorespiratory system [358,359]. Aware of the literature debate around Kinesio taping's effect on musculoskeletal disorders [360-365], we decided to utilize it as a support therapy in the pain management administered through antalgic therapy based on the evidence reported by many authors about the positive effect of Kinesio taping application in conjunction with exercises [364-373], and its validity in the treatment and prevention of spine injuries [374-377]. Nevertheless, for low back pain treatment, the kinesiological approach, i.e., exercise administration, is strongly suggested because it effectively generates improvements compared with manual therapy or conservative treatment [378-380]. Non-specific LBP, in some cases, may recover without treatment administration; however, in our case, the presence of early spine OA in conjunction with the intense physical effort throughout the enduro championship may have determined the acute LBP, which required treatment to recover spine mobility and strength. Sports physicians are recommended to harvest more data regarding this sport and its related injuries to prevent the development of chronic, disabling diseases from motorcycle overuse and to most effectively address the physical preparation and treatment. Physicians ordinarily suggest pharmacological treatment with or without infiltration to reduce pain and improve the mobility of the spine in patients with OA. In this case, we reported premature spine osteoarthritis in a competitive enduro motorcyclist treated with a conservative, non-invasive, and efficient kinesiological approach. Based on our insights, this scientific contribution could help address this condition and raise questions about a possible negative role of jolting stimulus stress on the spine that might exist among these athletes.

Certain limitations should be considered, however, when interpreting these findings. First, this is a case study, so we observed that specific condition in one person; second, the results cannot be generalized to the whole osteoarthritic population; third, we cannot unequivocally correlate the early osteoarthritis spine with motorcycling vibrations.

4. Conclusions

This is a clinical report in which early spine osteoarthritis from enduro motorcycle overuse is present. The report supports previous findings on early spine osteoarthritis and motorcycling vibrations. This study hypothesizes a possible relationship between long-time vibration exposure and early spine osteoarthritis. Furthermore, we advise a preventive approach and the creation of specific medical examination guidelines for these athletes. Furthermore, to reduce pain and inflammation and improve the spine mobility and muscle strength of these patients/athletes, a non-invasive kinesiological approach should be recommended for the long term. Additional research concerning the Kinesio taping application is required to establish a guideline accepted by the entire scientific community. A specific investigation of the causality between long-time vibration exposure and early spine osteoarthritis is needed.

Running footwear and impact peak differences in recreational runners

Federico Roggio [1,2] , Bruno Trovato [1], Marta Zanghì [1], Luca Petrigna [1], Gianluca Testa [3], Vito Pavone [3] and Giuseppe Musumeci [1,4]

[1] Department of Biomedical and Biotechnological Sciences, Section of Anatomy, Histology and Movement Science, School of Medicine, University of Catania, Via S. Sofia 97, 95123, Catania, Italy.

[2] Sport and Exercise Sciences Research Unit, Department of Psychology, Educational Science and Human Movement, University of Palermo, Via Giovanni Pascoli 6, Palermo, 90144, Italy.

[3] Department of General Surgery and Medical Surgical Specialties, Section of Orthopedics and Traumatology, AOU. Policlinico-Vittorio Emanuele, University of Catania, Via Santa Sofia 78, 95123 Catania, Italy.

[4] Research Center on Motor Activities (CRAM), University of Catania, Via S. Sofia 97, 95123, Catania, Italy.

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1. Introduction

Running is one of the most common ways to practice physical activity, and it is estimated that almost 50 million Europeans practice this sport to stay healthy [381]. The typical strike pattern among runners is the rearfoot, defined as a pattern where the runner contacts the ground with the lateral portion of the heel [382]. Xu et al. [383] found that a rearfoot strike pattern has a higher general biomechanical load on the knees, patellofemoral joint, and over the ground. Rearfoot runners deal with a repeated ground impact during the first 50 milliseconds of the stance phase, an abrupt collision around 1.5-3 times the bodyweight [384]. The magnitude of this high loading impact travels all over the body and can contribute to the onset of running-related injuries; modern running shoes can mitigate the perception of impact, although it may not disappear entirely [384].

Recreational runners may also encounter this occurrence due to potential inexperience. Furthermore, rearfoot runners appear to produce a higher magnitude and earlier vertical impact peak timing than forefoot runners [384]. A meta-analysis [385] conducted among different categories of runners stated the incidence of running-related injuries with a weighted estimation of 7.7 (95 % CI 6.9–8.7) per 1000 h of running in recreational runners. Different authors support the idea that alterations of running biomechanics may induce them to repetitive atypical load to the tendons that is associated with an increased risk of lower limb tendinopathies such as Achilles tendinopathy, iliotibial band syndrome, plantar fasciitis, and posterior tibial tendon dysfunction [386-389].

Different types of running shoes, i.e. minimalist or maximalist, have been produced to overcome the risk of running-related injuries [390], based on a difference in the thickness of the forefoot and heel parts of the sole, called heel-to-toe drop (HTD). The shoes with a low HTD have a measure of 4-6 mm, while the shoes with a high HTD can reach the 10-12 mm. High impact peak is believed to be strictly related to running-related injuries [384], so the need to produce shoes with an increased cushioning, i.e., high HTD. However, this condition is still debated because there is no clear evidence that high cushioning can reduce impact peak [391]. Furthermore, different HTD can induce different running biomechanics such as increased vertical loading rate in low HTD [392], changes in the foot inclination angle and therefore, changes in the running biomechanics [393].

The evaluation of running biomechanics is often performed to estimate the characteristics of the running pattern to understand the relationship between kinematic variables that may predispose the runners to experience injuries. In this context, the optoelectronic infrared multi-camera motion analysis system is the most accurate approach to analyze the movements [394]. However, these systems are expensive and subject to certain conditions such as a dedicated laboratory, long preparation times, or highly trained clinicians identifying the anatomical landmarks correctly to place the reflective markers [29,193]. To overcome some of these conditions, instrumented treadmills [395-397] and inertial measurement unit (IMU) systems [122,398] are spreading as a valid alternative to accomplish gait or run analyses in different environments, avoiding some of the previously mentioned conditions. In the context of recreational runners, this approach can identify the alterations of the motion without excessive clinical effort. Knowing which biomechanical variables result altered during running gait can guide runners or coaches toward an intervention to avoid the impact peak presence [399]. These new motion analysis technologies can provide a cost-effective and easily reproducible approach thanks to a 3D camera that detects kinematic variables and the load cells to measure vertical ground reaction force, used to derive spatiotemporal parameters.

This study aimed to collect runners' characteristics concerning the footwear and then employed an instrumented treadmill with a 3D camera to analyze spatiotemporal and kinematics parameters of recreational runners. Furthermore, the runners have been classified based on the presence or absence of the impact peak, and then we investigated the correlation among the measured parameters.

2. Materials and Methods

This retrospective study involved thirty male adult half-marathon recreational runners (mean ± SD); age 46.28 ± 6.49 years, height 174.59 ± 5.87 cm, body mass 71.86 ± 6.77 kg, and BMI 23.56 ± 1.69 kg/m^2. The running experience is 9.4 ± 2.2 years, and the km-average per week is 13 ± 3.4 km. Participants were recruited voluntarily at the Research Center in Motor Activities (CRAM), University of Catania. The exclusion criteria are recent joint trauma, pain during running, history of professional running. Once we performed the running analysis, we classified the participants in impact peak presence (IP) (n = 16) and impact peak absence (n-IP) (n = 14). The data collection was approved by the Research Center in Motor Activities (CRAM), University of Catania (protocol n.: CRAM-09-2020, 16/03/2020), in accordance with the Declaration of Helsinki. All participants provided informed consent before participating.

2.1. Data collection

A markerless system was used to analyze the kinematic movements in the sagittal plane. The Walker View (Tecnobody® Dalmine, Italy) is a treadmill with a markerless system that automatically identifies anatomical landmarks through AI [29] valid for both spatiotemporal parameters and angular displacements [396,400,401]. It is composed of an instrumented treadmill equipped with eight load cells (composed by strain gauges, sampling frequency 100 Hz) and a 3D camera for motion capture (Microsoft Kinect v2, sampling frequency 30 Hz) available for sports, medicine, rehabilitation, and gait analysis. Eltoukhy et al. [401] reported excellent interclass correlations coefficients (> 0.75) for agreement (ag) and consistency (cn) by comparing the measurements of this camera with a BTS optoelectronic system. Total hip ROM, ag= 0.80, cn=0.86; total knee ROM, ag=0.80, cn=0.82; step length, ag=0.67, cn=0.87; contact time, ag=0.82, cn=0.97; CoM vertical displacement, ag=0.83, cn=0.83 [401]. Ankle dorsiflexion/plantarflexion, initial contact, and toe-off were collected through two inertial measurements units (IMU) placed over the feet with a belt, connected via bluetooth to the system, weight 47g, sampling frequency 100 Hz. For the running analysis, participants were advised to wear shorts, a t-shirt, and their own running shoes, leaving the anatomical landmarks uncovered. Before the test, they practiced 10 minutes of warm-up on the treadmill at a self-paced speed according to their overground running speed. We used the adopted speed to set the run analysis lately. The test was performed by keeping the erect position for a few seconds so that the system could locate the anatomical landmarks correctly. Once the exam was started, the runners had to run for 10 minutes, where the speed slowly increased until their suitable speed was reached. Then, the kinematics record was performed for 60 seconds. We divided the participants into the IP or n-IP groups based on the presence of the impact peak by visualizing the gait graph of the vertical load provided by the Tecnobody software.

Furthermore, runners completed a questionnaire to collect specific conditions referred to the footwear and investigate if they experienced injuries during the last year. We asked them information about the number size of the shoes, how often they change the shoes, if they use any particular sole, if they experience pain after a training, kilometers per week, if they experienced injuries during the last year and if yes the injury location and severity.

2.2. Data processing

The integrated software (i.e., TecnoBody Management System, Bergamo, Italy) analyzes spatiotemporal and kinematic parameters. The system records each phase of the running cycle and then produces the report showing the averages of the joint ROM of the trunk, hip, knee, ankle, and maximum extension and flexion values for each joint for both limbs. The quaternions of each anatomical part are calculated starting from the positions of the articular joints. Then, they are decomposed into Euler angles following the International Society of Biomechanics guidelines for the angle calculation [402]. Hereinafter we refer to joint parameters as maximum extension and flexion. Spatiotemporal parameters included stride length, step time, step cycle, vertical center of mass displacement (CoM), calculated with the segmental analysis method using lower body kinematic data and anthropometric measurements [403]. Furthermore, we calculated steps per minute (spm) as D / MSL / T, where D corresponds to distance traveled expressed in meters, MSL is the mean of stride length of the left and ride feet expressed in meters, T is the total time of the run analysis, expressed in minutes.

2.3. Data analysis

Statistical analysis was performed using R Project for Statistical Computing (Vienna, Austria). The data from the questionnaire have been discussed with descriptive analysis while the data of running biomechanics have been processed through inferential analysis. The Shapiro-Wilk test verified the normality distribution; the Levene's test verified the homogeneity of the variance; the Student t-test and the Mann-Whitney U test determined whether any significant differences in kinematics, spatiotemporal anthropometric, and demographic parameters existed between the groups. The Mann-Whitney U test was used since not all the variables were found to be normally distributed through the Shapiro-Wilk test. Cohen's effect size (d) was applied to identify meaningful differences between the groups. Based on Cohen's criteria, $d \geq 0.80$ (absolute value) was considered a large effect size, and $d \geq 0.50$ (absolute value) was considered a medium effect size.

Pearson correlation coefficients (r) between variables have been calculated for each group separately to determine which kinematic and spatiotemporal parameters are related. A correlation matrix was arranged to present the existing correlations. Only significant correlations according to p-value < 0.05 have been considered.

3. Results

Participant characteristics are in Table 1; no statistical differences were present among the two groups concerning the anthropometric characteristics.

Table 1. Participants information.

Table 1: Participants information

	Mean angle (SD)	
	IP group	n-IP group
Age (years)	47.19 (6.85)	45.15 (6.09)
Height (cm)	174.38 (5.10)	174.85 (6.91)
Body mass (kg)	70.81 (6.06)	73.15 (7.60)
BMI (kg/m2)	23.27 (1.45)	23.92 (1.94)
Weekly Km (km)	40.00 (6.32)	44.20 (14.97)
Weekly trainings (days)	3.34 (0.52)	3.50 (1.05)

IP group= impact peak presence; n-IP= impact peak absence; BMI= body mass index

3.1. Spatiotemporal

Spatiotemporal results are reported in Table 2. The n-IP runners have a shorter stride length (105.50 ± 20.50 cm) compared to IP runners (119.30 ± 11.10 cm) with a large effect size (d= -0.84). Contact time does not significantly change (n-IP 0.30 ± 0.04 , IP 0.30 ± 0.02, d= 0.06), spm significantly vary between n-IP group (163 ± 13.90 spm) and IP group (170 ± 11.40 spm) with a medium effect size (d= -0.51). The vertical CoM displacement results higher in the n-IP group (n-IP 6.20 ± 1.00 cm, IP 5.80 ± 1.40 cm) with a small effect size (d= 0.35). Also step cycle time, defined as how many steps in 1 second, did not considerably change (n-IP 1.43 ± 0.09 c/s, IP 1.46 ± 0.09 c/s , d= 0.33). Finally, running speed was not statistically different between the groups (n-IP 11.90 ± 1.50 km/h, IP 11.20 ± 2.90, d=-0.32).

Table 2. Spatiotemporal parameters of recreational runners.

	Mean angle (SD)				
	IP group	n-IP group	Sig.	Effect size (d)+	U3+
Stride length (cm)	105.50 (20.50)	119.30 (11.10)	0.02*	-0.84	80%
Contact time (s)	0.30 (0.04)	0.30 (0.02)	0.40	0.32	-
SPM	163 (13.90)	170 (11.40)	0.17	-0.51	69.5%
CoM displacement (cm)	6.20 (0.98)	5.80 (1.39)	0.37	0.35	-
Step cycle (c/s)	1.43 (0.09)	1.46 (0.09)	0.46	-0.33	-
Speed (km/h)	11.20 (2.88)	11.90 (1.50)	0.18	-0.32	-

*IP group= impact peak presence; n-IP= impact peak absence; + Cohen's values; ++Cohen's U3 describes the proportion of distribution overlap; Sig. according to t-test for normal data and Mann-Whitney U for non-normal data (* < 0.05, ** < 0.01) . Note: bold numbers indicate a large effect size between groups (d > .80). Bold and italic numbers indicate a medium effect size between groups (d > .50).*

3.2. Kinematic parameters

Several differences were found between the impact peak and the no-impact peak groups. Three variables demonstrated a large effect size (d) greater than 0.80, while two proved a medium effect size (d) greater than 0.50. The means and effect sizes of the sagittal plane parameters are reported in table 3. The trunk inclination did not statistically differ between the two groups. Hip flexion showed a statistically different range of motion in the n-IP group compared to the IP group (n-IP 32.30° ± 10.20, IP 40.40° ± 9.50) with a large effect size (d= -0.82). The hip extension shows a similar trend with a range of motion reduction in the n-IP group (n-IP 27.70° ± 4.60, IP 30.20° ± 3.90), reporting a medium effect size (d= -0.58). Knee flexion shows only a non-statistical difference with small effect sizes in both flexion and extension. The ankle dorsiflexion indicates a statistical difference between the groups. The n-IP group has a reduced range of motion (13.40° ± 7.20), compared to the IP group, which shows a completely rearfoot strike pattern (20.80° ± 5.50), with a large effect size (d= -1.17). Meanwhile, ankle plantarflexion between the groups shows a statistical difference however with a small effect size. Initial and final foot contact has been evaluated in the frontal plane. The foot inversion at initial contact statistically differs in the n-IP group compared to the IP group (n-IP 17.30° ± 3.80, IP 14.30° ± 3.50) with a large effect size (d= 0.83). A reduced foot inversion is present at the toe-off phase (n-IP 3.60° ± 3.00, IP 5.00° ± 2.70) with a medium effect size (d= -0.50).

Table 3. Kinematic parameters of recreational runners.

Joint Excursion	Mean Angle (SD)				
	IP group	n-IP group	Sig.	Effect size (d)+	U3++
Trunk					
Flexion	11.40° (2.30)	11.60° (2.40)	0.31	-0.06	-
Hip					
Flexion	40.40° (9.50)	32.30° (10.20)	0.03*	-0.82	79.3%
Extension	30.20° (3.90)	27.70° (4.60)	0.12	-0.58	71.9%
Knee					
Flexion	86.60° (17.10)	88.74° (15.80)	0.73	0.13	-
Extension	5.60° (3.50)	4.90° (3.40)	0.59	-0.20	-
Ankle					
Dorsiflexion	20.80° (5.50)	13.40° (7.20)	0.003**	-1.17	87.9%
Plantarflexion	50.30° (4.60)	51.50° (4.70)	0.03*	0.25	-
Foot					
Inversion at IC	14.30° (3.50)	17.30° (3.80)	0.03*	0.83	79.6%
Inversion at TO	5.00° (2.70)	3.58° (3.00)	0.13	-0.50	69.2%

*IP group= impact peak presence; n-IP= impact peak absence; + Cohen's values; ++Cohen's U3 describes the proportion of distribution overlap; Sig. according to t-test for normal data and Mann-Whitney U for non-normal data (* < 0.05, ** < 0.01); IC= initial contact; TO= toe-off. Note: bold numbers indicate a large effect size between groups (d > .80). Bold and italic numbers indicate a medium effect size between groups (d > .50).*

3.3. Footwear and injuries

Footwear differences were present among the runners, with a substantial difference in the HTD drop between IP and n-IP groups. All the information are reported in Table 4. The proportion of HTD drop of the runners belonging to the IP group is 14.29% (8 mm), 42.86% (10 mm), and 42.86% (12 mm). Whereas the proportion of HTD drop of the runners belonging to the n-IP group is 57.14% (4 mm), 14,29% (6 mm), 14.29% (8 mm), and 14.29% (10 mm). Furthermore, we calculated the mean weight of the shoes, IP group have a mean shoe weight of 273.43 ± 31.80 g, while the n-IP group have 244.0 ± 39.40 g. Concerning the injuries, 57.14% of n-IP runners did not experience an injury during the last year, while IP runners experienced an injury at least 1 (42.86%) or 2 (42.80%) times during the last year. Furthermore, the latter experienced a severe condition of the injury, the 50% of them reported the need for physical therapy to recover from the trauma.

Table 4. Specific conditions referred to the footwear and the incidence of injuries

	n-IP group	IP group
Shoes size		
Same as the foot size	28.57%	14.29%
½ point greater	14.29%	57.14%
1 point greater	57.14%	28.57%
New shoes change		
After 600-800 km	71.43%	71.43%
After 800-1000 km	28.57%	-
When the shoes gets ruined	-	28.58%
Feet pain after training		
Yes	14.29%	57.14%
No	85.71%	42.86%
Suspend due to injury (in one year)		
0 times	57.14%	14.29%
1 time	28.57%	42.86%
2 times	14.29%	42.80%
Common injury location		
Back	7.14%	-
Hip	7.14%	-
Hamstrings	21.43%	16.67%
Knee	7.14%	41.67%
Calf	21.43%	16.67%
Achilles tendon	-	8.33%
Foot	-	8.49%
None	35.72%	8.33%
Injury severity		
None	42.86%	12.50%
Mild, needed a little rest	28.57%	25.00%
Moderate, extended rest and ice	28.57%	12.50%
Severe, needed medications or physiotherapy	-	50.00%

3.4. Correlation matrix

Both groups underwent the Pearson correlation coefficients (r) analysis. The results are graphically showed in the correlation matrices, Figure 1. The IP group present an overall incidence of negative correlations between the variables. Only moderate to strong correlations ($r > \pm 0.50$) with a $p < 0.01$ are discussed. Are negatively correlated: Hip extension with knee extension (r= -0.751); CoM vertical displacement with knee extension (r= -0.658); contact time with step per minute (r= -0.729); CoM vertical displacement with step per minute (r= -0.821); step time with CoM vertical displacement (r= -0.847); contact time with step time (r= -0.699). Are positively correlated: stride length with hip extension (r= 0.569); stride length with knee flexion (r= 0.724); stride length with foot dorsiflexion (r= 0.526); CoM vertical displacement with knee flexion (r= 0.550); step time with knee extension (r= 0.630), Figure 1a.

Conversely, the n-IP group presents an overall incidence of strong positive correlations between the variables. Are positively correlated: hip flexion with foot inversion at initial contact (r= 0.661); hip flexion with stride length (r= 0.842); hip flexion with step per minute (r= 0.765); hip flexion with step time (r= 0.638); hip extension with stride length (r= 0.704); knee extension with foot inversion at initial contact (r= 0.596); knee flexion with stride length (r= 0.819); knee flexion with step per minute (r= 0.691); foot inversion at initial contact with step per minute (r= 0.567); foot inversion at toe-off with CoM vertical displacement (r= 0.581); stride length with step per minute (r= 0.761); running speed with hip flexion (r=0.85), hip extension (r=0.533), knee flexion (r=0.794), spm (r=0.785) and step cycle (r=0.684). While, the only one variable showing strong negative correlations for n-IP group is contact time with: hip flexion (r= -0.839), knee flexion (r= -0.852), foot inversion at initial contact (r= -0.701), stride length (r= -0.798), step per minute (r= -0.919), running speed (r=-0.788), Figure 1b.

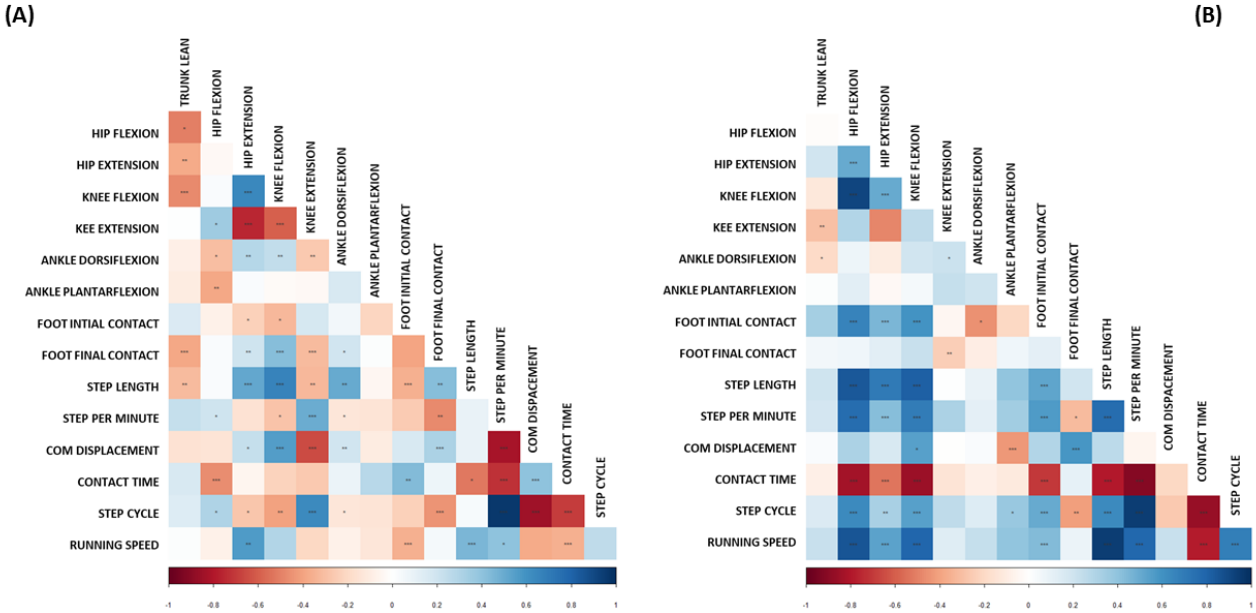

Figure 1. *correlation matrices of impact peak presence group (A) and impact peak absence group (B). The figure (A) presents a majority of negative correlations (red color); the figure (B) presents a majority of positive correlations (blue color). *** = $p < 0.01$, ** = $p < 0.05$, * = $p < 0.1$. The IP group presents a general occurrence of negative correlations, according to matrix color. The n-IP group generally presents positive correlations.*

4. Discussion

This study aimed to analyze the running pattern of recreational runners through a markerless system and whether it has a connection with the presence/absence of impact peak. We measured them according to differences in 3D gait kinematics of the hip, knee, ankle, foot, and spatiotemporal parameters. The sample classification for the presence or absence of the impact peak adequately matched the runners according to the main biomechanical joint characteristics of rearfoot (figure 2a) and forefoot runners (figure 2b) [383]. The results suggest that recreational runners without the impact peak present a shorter stride length, reduced hip flexion, increased foot inversion at initial contact, and predominantly reduced ankle dorsiflexion at initial contact compared with the counterpart.

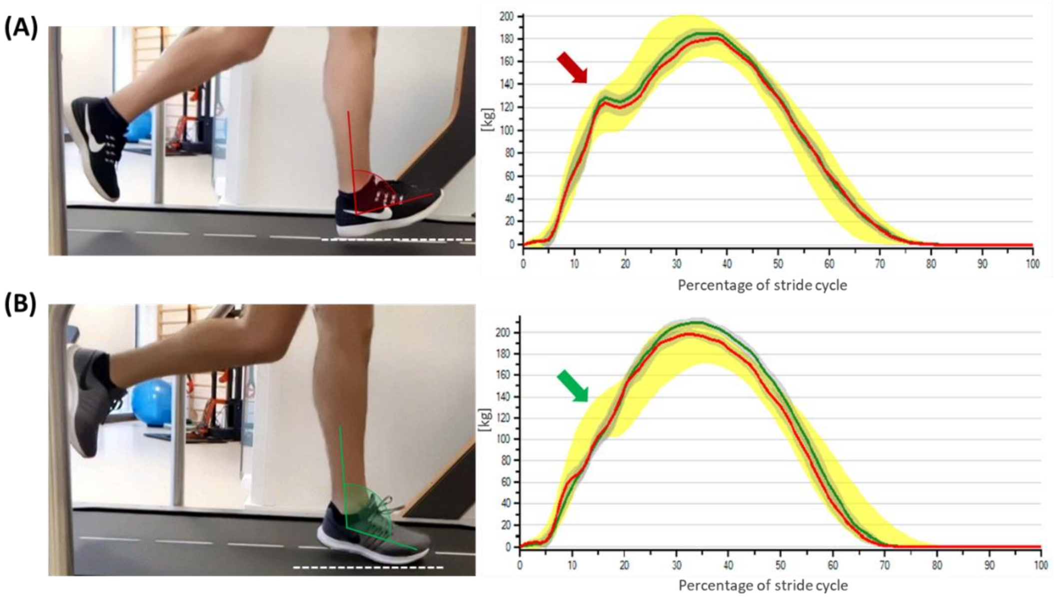

Figure 2. *The impact peak force graphs showing impact peak presence (A), the red arrow specifies the impact peak occurrence; and impact peak absence (B), the green arrow specifies the impact peak absence. The red line represents the left side of the body, the green line represents the right side, the yellow band represents the values of normality.*

In our sample, runners that exhibited a reduction in stride length do not present impact peak. Various authors [404,405] agree that shock attenuation may change only when stride length changes. We support that a plausible association between impact peak and stride length may vary due to leg geometry changes as stride length changes [404]. Differences in step frequency are present between the groups. The n-IP group has a reduced step frequency (163 ± 13.90 spm) than the IP group (170 ± 11.40 spm). It is lower from several studies [384,406,407], whereas the impact peak absence is correlated to an SPM frequency of 180 spm. This could be affected by the running speed of the study sample because it was self-selected by the runners, and probably it was not their maximal speed. Secondly, there is also a positive correlation between step frequency and hip flexion, hip extension, and knee flexion. Since all values are reduced in the n-IP group, we hypothesize that this reduction could be related to step frequency decrease. Even if the CoM vertical displacement has a small effect size, there is still a noticeable difference, whereas the n-IP group tends to present a higher CoM displacement, although generally, it is lower than recreational runners from two different studies [408,409]. Furthermore, Shih et al. [408] stated that the vertical displacement of CoM does not statistically differ among barefoot and shod runners or rearfoot and forefoot strikers. Our sample shows a reduced vertical displacement. The increased hip extension may explain a CoM drop during the single support phase, which determines a reduced CoM vertical displacement. Secondly, the use of the treadmill could be a reason for a reduced CoM displacement, whereas alternative running environments can add moderate effects on the vertical displacement [410].

The study findings show no differences in the trunk forward lean between n-IP and IP groups. This phenomenon can be explained because participants ran at their self-paced speed, and when this condition is met, runners are not prone to increase their trunk inclination [411]. Weinhandl et al. [412] and Sah et al. [413] described the trunk flexion increase as a compensatory strategy to modulate shock attenuation during the run, while Hart et al. [414] showed that paraspinal muscular fatigue could increase trunk flexion. These statements are disagreeable as there is no difference in trunk inclination between n-IP and IP groups. The runners had not trained before the data acquisition, so fatigue cannot be an important factor. [415,416]. The WalkerView can easily detect the trunk inclination, and therefore, it allows to easily educate recreational runners, increasing trunk flexion and reducing patellofemoral joint stress, as the literature suggests [34, 35].

Our results show a reduction in hip flexion and increased hip extension in the n-IP group, compared to other studies [417,418]. Hip flexion data differs from dos Santos et al. [419], where the hip flexion appears to increase from rearfoot to forefoot runners. Even if the strike pattern did not categorize our sample, the n-IP group's ankle dorsiflexion corresponds to midfoot/forefoot runners. Consequently, a hip flexion reduction was demonstrated in those without impact peak [386]. Knee flexion is similar to Koblbauer et al.'s findings [418], in contrast to Rueda et al.'s study [417], where it appears reduced. A possible explanation may be the reduced hip flexion limiting knee motion and the recreational runners' tendency to reach the surface with less knee flexion due to foot placement being further away from the center of mass [417].

Wang et al. [406] evaluated the changes in lower extremity biomechanics in recreational runners after a 12-week training protocol. By comparing the ankle angle at initial contact, our IP group is comparable to this study's pre-training group, while the post-training group is similar to our n-IP ankle group angle at initial contact. That value lies within the range of 8°-15°, reported as the correct ankle range at initial contact to prevent peak force impact [420]. Our n-IP group did not show a real forefoot strike pattern; nevertheless, adopting a midfoot strike pattern can reduce the loading rate by around 50% and perhaps altogether remove the impact peak [384,421,422]. Moen et al. [423] highlighted that reducing excessive ankle dorsiflexion can increase the stress on the shank muscles and joints. However, as our sample group has more than ten years of running experience, this should not be a significant issue. This precaution must be carefully considered in those who intend to change their strike pattern.

Our results indicate that runners overcoming the impact peak presence exhibit a reduced hip range of motion for flexion and extension. A slight increase of knee flexion potentially supports the hip flexion reduction. The findings on ankle dorsiflexion at initial contact align with all the previous studies [383] investigating this particular joint as the leading factor of impact peak reduction. An increase of foot inversion at initial contact is also present. Both recreational runners and trainers should be aware of excessive hip flexion, ankle dorsiflexion, stride length, and reduced foot inversion at initial contact because these factors may predispose runners to running-related injuries. However, running-related injuries are not so directly correlated with foot strike patterns. Burke et al.[424], recently highlighted low evidence to suggest a relationship between these two conditions. Accordingly to this assumption, we observed the impact peak predominantly in a sample of rearfoot runners; however, we do not speculate about the relationship between the strike pattern and the injury onset.

Secondly, we surveyed the runners about the footwear to estimate the main characteristics based on the classification in IP and n-IP groups. The IP group generally wears shoes with a high HTD and they are used to buying shoe ½ point (EU sizes) greater than the usual number of non-sportive shoes. Meanwhile, the n-IP generally wears shoes with a low HTD and almost all of them are used to buying the shoes 1 point greater than the usual number which may explain why 85.71% of them do not experience pain at the feet at the end of training. Concerning the incidence of injuries, the IP group present a greater proportion of runners that experienced an injury during the last year, with the knee as the location with the higher incidence. The HTD should not influence the injury risk, actually, low HTD could be associated with higher injury risk in regular runners [425]. The information collected about the injury location is alike to Kakouris et al. [426] who found the knee as the highest location of injury for the IP group. Meanwhile, the n-IP group did not respect the previous trend, presenting hamstrings and calf muscles as the zone with the highest proportion. However, we cannot unequivocally correlate the use of different footwear with the incidence of impact peak because we observed the behaviour of recreational runners concerning the use of the shoes and their aspects rather than analyzing different shoes in biomechanics analysis.

This study's results have potential scientific relevance for runners' training programs with impact peak. When a recreational runner’s hip extension is around 40°, ankle dorsiflexion is around 20°, and initial foot contact is around 14°, could fit into the profile of a runner with an impact peak. Furthermore, a stride length exceeding 120 cm can negatively affect the performance of recreational runners.

Certain limitations should be considered, however, when interpreting these findings. First, we analyzed only sagittal kinematics through a 3D markerless system, whose accuracy cannot be compared with marker-based systems. Secondly, the analysis took place on a treadmill, so results have to be considered carefully compared to overground running.

Further studies should include a more significant number of participants, ideally in an outdoor setting, and investigate the differences in the running pattern with own shoes compared with standard shoes. Furthermore, attention is required, as recreational runners are highly likely to get injured [427]. Many studies examined only specific running characteristics [428], omitting any possible interaction between spatiotemporal, kinetic, kinematic parameters, and footwear. Awareness of the specific biomechanical factors behind the onset of pain or injury can help clinicians select a well-suited treatment strategy. However, it is challenging to manage appropriate injury prevention programs without further studies regarding biomechanical factors that precede an injury [429].

5. Conclusions

Recreational runners without impact peak commonly run with low HTD drop shoes, and exhibit a shorter stride length and a slight increase of CoM vertical displacement. Trunk forward lean does not differ between the groups. Hip flexion is reduced, balancing the ankle dorsiflexion and foot inversion at initial contact. Finally, this study emphasizes an approach based on a 3D motion capture markerless system analysis, which may easily and quickly elucidate the complex correlations of the impact peak presence. Sports physicians and coaches are called upon to collect more information about running-related injuries in recreational runners to prevent possible chronic disabling diseases. Furthermore, it is essential to address training programs toward a well-suited approach because recreational runners are more numerous than professionals. We aspire to provide new contributions to the scientific community about running aspects through the 3D analysis to avoid injuries and enhance the performance of recreational runners.

Postural Evaluation in Young Healthy Adults through a Digital and Reproducible Method

Bruno Trovato [1], Federico Roggio [1,2] , Martina Sortino [1,], Marta Zanghì [1], Luca Petrigna [1], Rosario Giuffrida [3] and Giuseppe Musumeci [1,4]

[1] Department of Biomedical and Biotechnological Sciences, Section of Anatomy, Histology and Movement Science, School of Medicine, University of Catania, Via S. Sofia 97, 95123, Catania, Italy.

[2] Sport and Exercise Sciences Research Unit, Department of Psychology, Educational Science and Human Movement, University of Palermo, Via Giovanni Pascoli 6, Palermo, 90144, Italy.

[3] Department of Biomedical and Biotechnological Sciences, Section of Physiology, School of Medicine, University of Catania, 95125 Catania, Italy

[4] Research Center on Motor Activities (CRAM), University of Catania, Via S. Sofia 97, 95123, Catania, Italy.

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Introduction

Posture is defined as the position acquired by the human body in various situations, opposing itself to the force of gravity and adapting to different environments [430]. Moreover, posture is essential for maintaining postural balance both in static and dynamic conditions. Remaining in a non-ergonomic position for an extended period can predispose people to manifest musculoskeletal pain [431], thus assuming good postures are considered necessary for general health, both at a musculoskeletal and psychological level [201]. Nowadays, the evaluation of human posture is performed consistently in healthcare clinics and fitness centers, considering that postural misalignments can cause individuals to manifest headaches, low back pain, neck pain, neurological pathologies,

and a reduction in overall psychological well-being [189]. Currently, the literature does not provide any gold standard procedure for postural assessment. The type of exams employed can vary from the visual evaluation with goniometers and plumb lines to motion capture systems like Vicon for the dynamic evaluation and 3D camera infrared systems like rasterstereography for the static one [432]. Regarding the feasibility of use of markerless system to assess human posture, rasterstereography is a system that generates a 3D model of the spine by calculating specific deformities analyzing the convexity and concavity of the spine [29]. It is commonly used to investigate the presence of scoliosis and considered reliable for the assessment of parameters like pelvic obliquity, thoracic kyphosis and lumbar lordosis angles[176,433]. However, this system has a high cost and it is difficult to implement in postural screening for the general population. Other valid tools like inertial measurement units (e.g. accelerometers, magneto inertial units) are also employed in the field of postural evaluation for the assessment of the thoracic kyphosis and the lumbar lordosis angles [434], and also for gait and balance assessment [435].
All the available methods for evaluating posture present some biases or disadvantages. The visual evaluation with the plumb line is cheap, but it requires specialized personnel, is prone to bias, and lacks scientific validation [436]. The use of goniometers is feasible for the measurement of the range of motion and angles of different joints with good reliability [437], it is low-cost and easy to perform, albeit it presents some methodological issues when assessing postural deviations [438], and it is considered useful for one postural variable examination at the time [432]. Marker-based advanced technologies are potentially available for clinicians that can provide highly accurate data on joint angles and translations; however, these evaluation systems are too expensive for the average clinic, and often they are employed for research purposes only [188].

In this heterogeneous scenario regarding the available postural evaluation tools, the advancement in image-based technologies comes in handy for clinicians and researchers who want to find a postural assessment system with good reproducibility and an affordable cost. Tablet and phone app for postural evaluation can fill this gap with different postural apps demonstrating promising results in the evaluation of the frontal plane [439], standing posture [438], angulation variables [188], and head shift in sagittal and frontal planes [189]; however, the literature is insufficient to confirm the quality of these methods. Considering that the complete visual evaluation of body posture with goniometers and the plumb line can be long and not free from biases, and taking into account the high costs of 3D systems, the use of mobile app could represent a quick, safe and accurate method to quantitatively evaluate the general posture for researchers and clinicians. Moreover, laboratory tests are often more expensive than the field based one [440], and adopting a mobile, affordable tool for postural assessment could benefit the primary prevention of the musculoskeletal disorders of the spine. The aim of this study is to present normative data about the digital posture evaluation through a mobile app Apecs and, moreover, evaluate the reproducibility.

2. Materials and Methods

2.1 Participants

We recruited and evaluated a sample of 100 healthy volunteers, 50 males and 50 females, with a mean age of 23.4 (standard deviation (SD) ± 6.2) years. Prior to testing, all participants were informed about the study procedure, risks, and benefits and provided written informed consent to participate in the study and use their data. The study followed the Helsinki declaration principles and was approved by the University of Catania (Protocol n.: CRAM-017-2020, 16/03/2020).

Exclusion criteria comprehended: past or current major musculoskeletal injuries, spine pathology, and neurological pathologies. All the participants selected after the oral interview underwent a static postural evaluation from an expert clinician (experience of 7 years) to confirm their eligibility for the study.

2.2 Study design

The evaluation took 30 minutes per participant and consisted of evaluating their health status and history of the previous condition that could meet the exclusion criteria at the University Laboratories. After the screening process, participants were asked to attend the laboratory always at the same time (between 10:00-12:00 a.m.). The postural evaluation was performed by three different operators with similar experience in postural analysis (3 to 4 years of experience). The mobile app Apecs-AI Posture Evaluation and Correction System®, (New Body Technologies SAS, Grenoble, France) (Apecs app), was used to acquire the images of the participants in the standing position. The participants were asked to dress in minimal clothing, shorts for men and shorts and bras for women, to minimize biases relative to wrong landmark positioning during the postural analysis; for the same reason, markers were placed by expert clinicians on the body of the participants in correspondence of the app's predetermined landmarks. Four pictures were captured, one for the anterior coronal plane, one for the posterior coronal plane, and two for the sagittal plane (left and right). Participants were instructed to place their feet the same width as the shoulders (Fig 1).

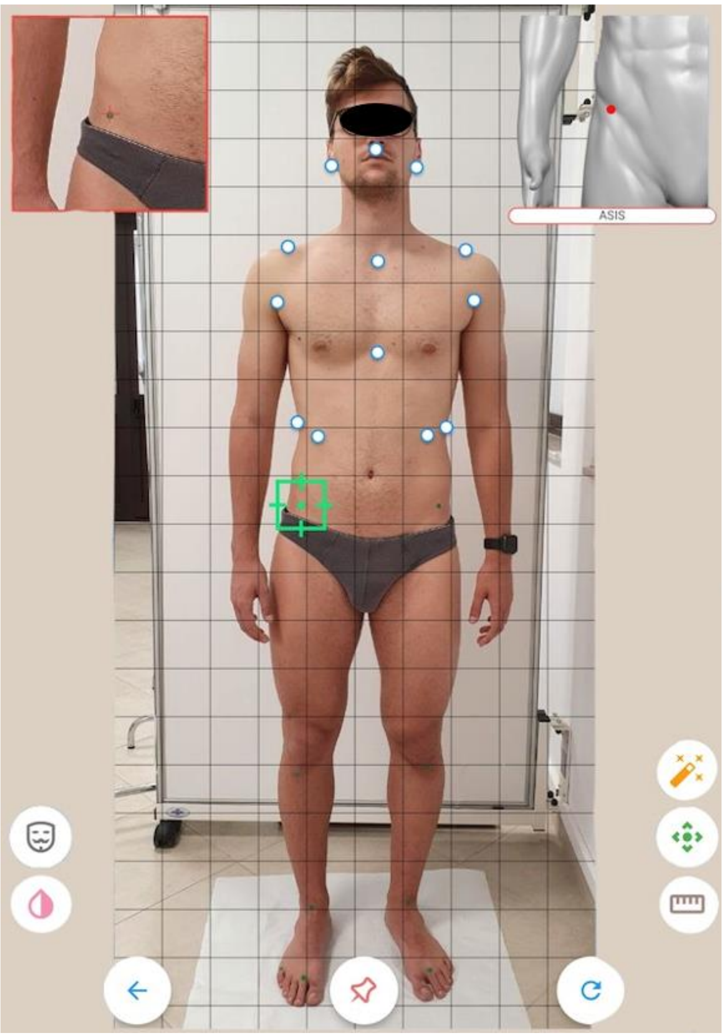

Figure.1 *Landmarks positioning*

To avoid any wrong camera leveling during the image acquisition, the app's interface shows a target that becomes green when the camera is leveled. After the picture is acquired, the app immediately steers the user to crop the image at the individual head and feet to minimize inconsistency in the proportion of different images. The Apecs app uses standardized digital landmarks and anatomical angles from one to four pictures, depending on the number of variables of interest to investigate. The app calculated 24 postural variables from the predetermined anatomical markers in the three planes of the space examined. Figure 2 shows the points evaluated in the anterior coronal plane (a), the sagittal plane (b), of the posterior coronal plane (c).

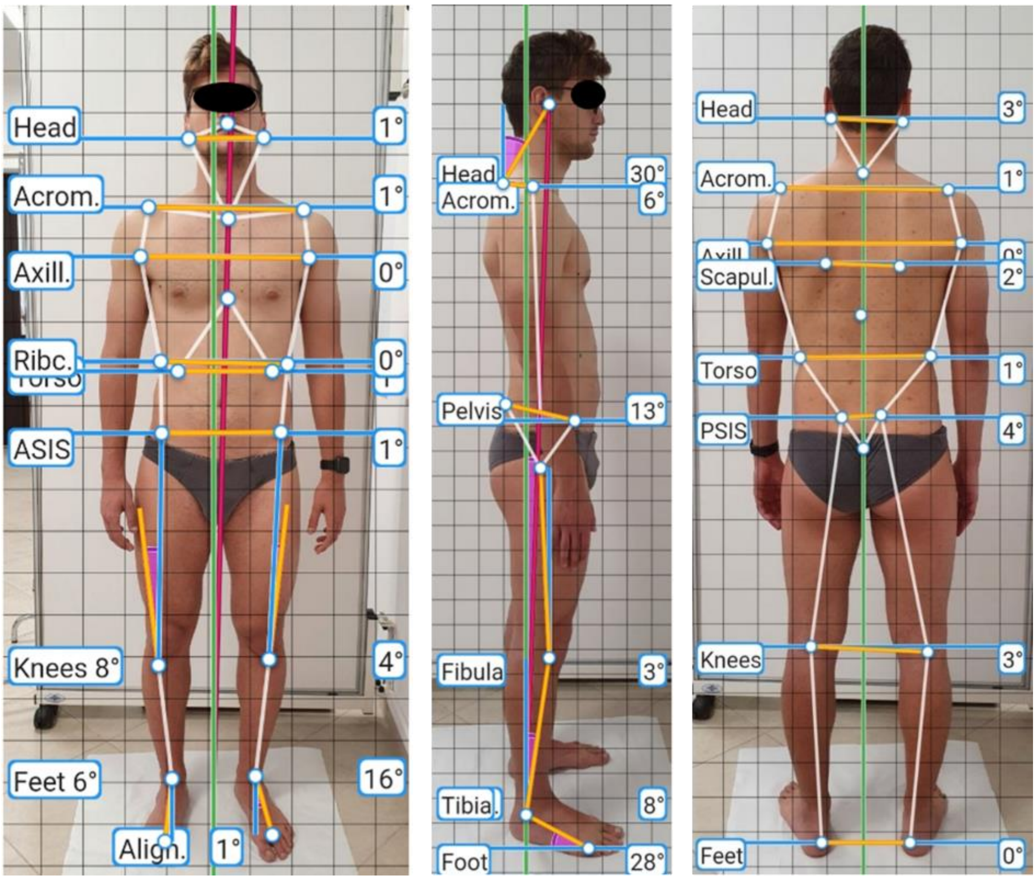

***Figure.* 2** *Evaluation of the anterior coronal plane (a); of the sagittal plane (b)of the posterior coronal plane (c)*

After the cropping phase, the app drives the user to position the digital markers, fostering this process with examples of the proper positioning with images. Table 1 shows all the anatomical landmarks taken into consideration by the app for calculating the postural variables.

Table 1. Anatomic landmarks and postural variables studied with Apecs

Plane of the space	Anatomical landmarks	Postural variables
Anterior coronal	Acromion Anterior axillary folds Anterior superior iliac spine Jugular notch Lobulus auriculae Lowest point of costal margin Midpoint between malleoli Most intended point of the trunk Philtrum Second metatarsophalangeal joint Tibial tuberosity Xiphoid process	Body alignment Head alignment Acromion alignment Axillae alignment Trunk inclination Ribcage tilt Antero superior iliac spine inclination Knee angle
Posterior coronal	Lobulus auriculae C-7 vertebrae Acromion Anterior axillary folds Inferior angle of the scapula T-6 vertebrae Most intended point of the trunk Posterior superior iliac spine Superior end of intergluteal cleft Popliteal fossa Calcaneal tuberosity	Body alignment Head alignment Shoulder alignment Axillae alignment Scapulae alignment Trunk inclination Postero superior iliac spines Knee angle Foot angle
Sagittal	Tragus C-7 vertebrae Acromion Posterior superior iliac spine Greater trochanter Lateral joint line Lateral malleolus Head of the fifth metatarsal bone	Body alignment Head alignment Acromion alignment Pelvic tilt Tibia shift Fibula alignment Foot angle

Statistical analysis

Data analysis comprised descriptive statistics to present the mean and standard deviation of the whole sample and divided by gender. Inferential statistics comprised the Shapiro-Wilk test to assess the data distribution; the student t-test was used to compare means between the male and female groups; statistical significance was set at $p \leq 0.05$. Cohen's effect size (d) was applied to identify meaningful differences between the groups. Based on Cohen's criteria, d 0.80 (absolute value) was considered a large effect size, and d 0.50 (absolute value) was considered a medium effect size. Post hoc power calculations were performed with G*Power v.3.1. Three qualified examiners were selected to perform the positioning of the markers and the postural analysis in two different parts of the day to assess the reproducibility of the app. The two-way mixed effect for absolute agreement was the model for calculating the intraclass correlation coefficient (ICC) for inter-rater agreement. The cut-off values for reproducibility based on a 95% confidence interval of the ICC estimate were < 0.5 poor, between 0.5 and 0.75 moderate, between 0.75 and 0.9 good, and > 0.9 excellent [441]. All the statistical analyses were performed with R Project for Statistical Computing (Vienna, Austria).

3. Results

Anthropometric measurements were taken for each subject and grouped by gender, with a mean male height of 175 (SD ± 5.6) cm, a mean female height of 164.6 (SD ± 6.5) cm, and a mean male weight of 75.5 (SD ± 8.8) kg and a mean female weight of 58,13 (SD ±7,41) kg.

The post hoc power calculation analysis with G*Power 3.1 returned a statistical power of 0,696 for our sample. The analysis of the digital anatomical landmarks collected with the Apecs app and the ICC values are presented in Table 2. The student t-test statistically indicated differences in the postural evaluation with the mobile app Apecs between males and females for specific variables. The postural variables with significant differences between male and female groups in the anterior coronal plane were axillary alignment ($p=0.04$), trunk inclination ($p=0.03$), and knee alignment ($p=0.01$). The female group presented more body inclination to the right than men, more trunk inclination, and a wider knee angle in the anterior coronal plane. The male group showed the worst results for the axillary alignment, which resulted in more deviating from the ideal alignment than the female group. In the sagittal plane, statistically significant differences were found for head inclination ($p= 0.04$), tibia shift ($p= 0.01$), and foot angle ($p< 0.001$). The head of the female group resulted more shifted from the ideal alignment compared to the male group and also showed a more accentuated anterior tibial shift. Instead, the male group presented a wider foot angle than the female group. No statistically significant differences were found between groups for the evaluation of the posterior coronal plane. According to Cohen's D there was a small effect size only for ribcage tilt (d= -0.35) in the anterior coronal plane, and for head alignment in the sagittal plane (d= -0.38); a large effect size for knee angle in the anterior coronal plane (d= -0.89), tibia shift in the sagittal plane (d= -0.95) and foot angle in the sagittal plane (d= 1.6). Figures 3, 4 and 5 show the box plots for gender differences in the three space planes.

The ICC showed promising results for inter-rater reproducibility, with values > 0.90 for thirteen out of the twenty-two postural variables examined and >0.60 for the other three variables; only six variables did not meet the cut-off criteria to be considered reliable. Table 2 shows the ICC for the postural variables evaluated.

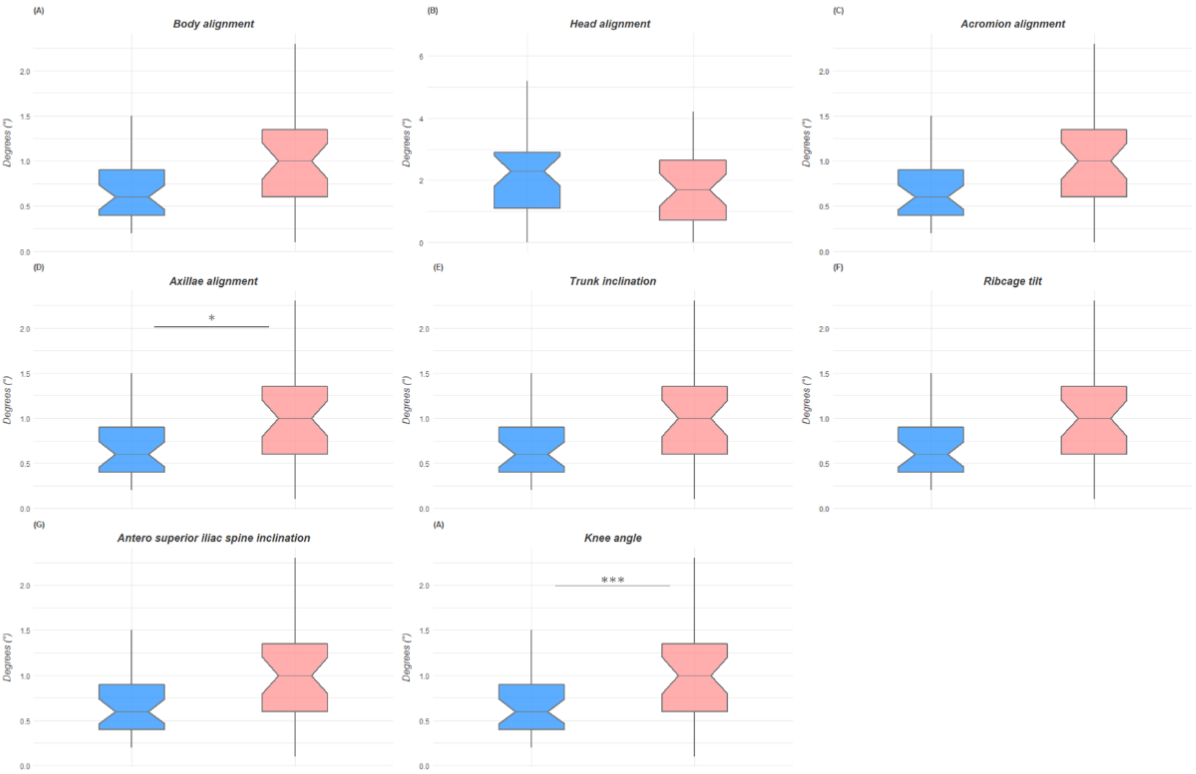

Figure 3. *Box plots of the differences between male and female groups in the anterior coronal plane with indication of significance*

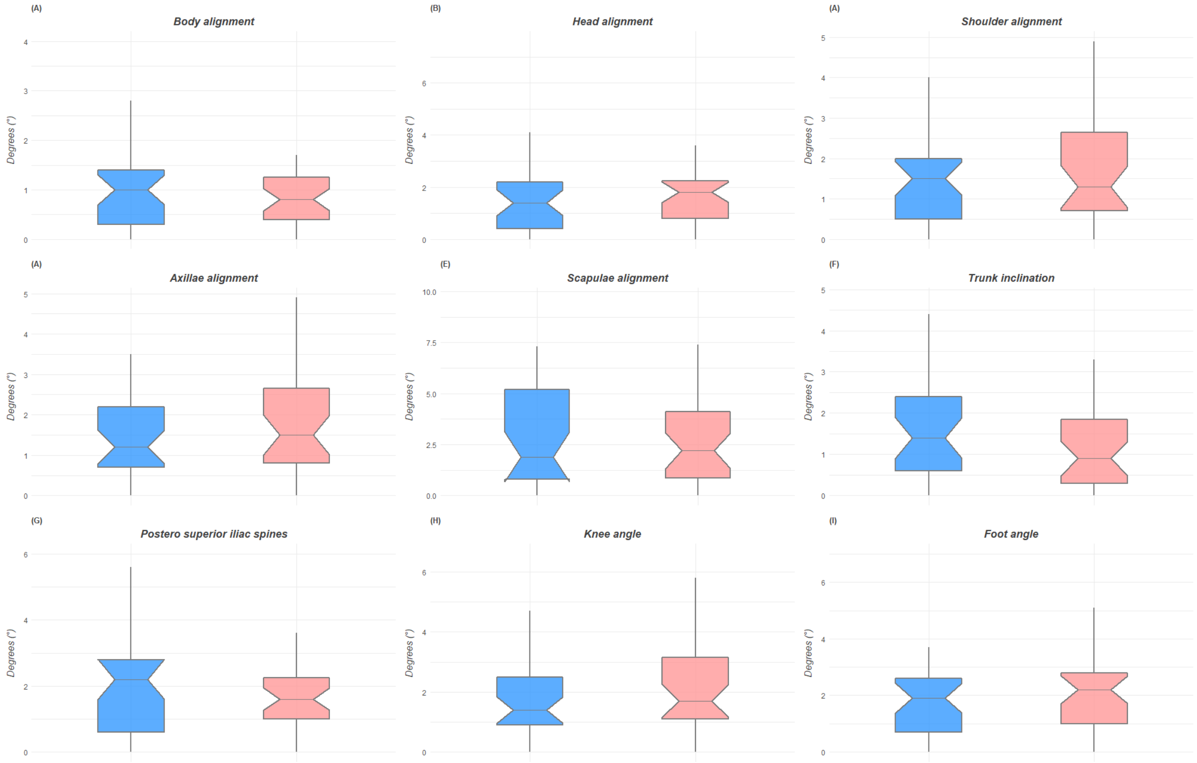

Figure 4. *Box plots of the differences between male and female groups in the posterior coronal plane*

Figure 5. *Box plots of the postural differences between male and female groups in the sagittal plane with indication of significance*

Table 2. Description of group means and ICC of the postural variables analyzed.

	Postural variables	Total	Males	Females	t-test	ICC	Cohen'd
		Mean ± SD	Mean ± SD	Mean ± SD			
Anterior coronal	Body alignment	0.9° ± 0.5	0.7° ± 0.4	1° ± 0.5	0.430	0.95	-0.54
	Head alignment	2° ± 1.4	2.2° ± 1.8	1.8° ± 1.4	0.989	0.51	0.25
	Acromion alignment	1.3° ± 1.0	1.4° ± 0.9	1.2° ± 1.1	0.423	0.91	0.17
	Axillae alignment	1.3° ± 1.0	1.4° ± 1.4	1.2° ± 0.8	0.044*	0.25	0.16
	Trunk inclination	1.6° ± 1.2	1.4° ± 1.3	1.8° ± 1.1	0.462	0.44	-0.29
	Ribcage tilt	1.9° ± 1.6	1.7° ± 1.2	2.2° ± 1.8	0.039*	0.93	-0.35
	ASIS inclination	2.3° ± 1.6	2.5° ± 1.7	1.5° ± 0.3	0.321	0.94	0.24
	Knee angle	6.2° ± 3.3	4.8° ± 2.9	7.5° ± 3.1	0.001***	0.93	-0.89
Posterior coronal	Body alignment	1°± 0.8	1° ± 0.8	0.9° ± 0 .8	0.717	0.84	0.07
	Head alignment	2.7° ± 1.5	1.6° ± 1.4	1.8° ± 1.5	0.652	0.30	-0.14
	Shoulder alignment	1.5° ± 1.2	1.4° ± 1.1	1.7° ± 1.4	0.444	0.93	-0.19
	Axillae alignment	1.6° ± 1.2	1.4° ± 1	1.7° ± 1.2	0.348	0.43	-0.26
	Scapulae alignment	2.7° ± 2.2	2.8° ± 2.3	2.7° ± 2.2	0.879	0.92	0.05
	Trunk inclination	1.4° ± 1.2	1.6° ± 1.2	1.3° ± 1.2	0.925	0.26	0.23
	PSIS inclination	1.9° ± 1.4	2° ± 1.6	1.8° ± 1.3	0.247	0.66	0.15
	Knee angle	1.9° ± 1.4	1.8° ± 1.2	2.1° ± 1.6	0.172	0.94	-0.23
	Foot angle	2.1° ± 1.6	1.9° ± 1.4	2.3° ± 1.8	0.151	0.75	-0.24
Sagittal	Body alignment	2.6° ± 1.2	2.6° ± 1.1	2.5° ± 1.3	0.691	0.94	0.1
	Head alignment	31.4° ± 5.4	30.3° ± 4.3	32.4° ± 6.2	0.047*	0.91	-0.38
	Acromion alignment	19.6° ± 12.3	19.9° ± 12.1	19.4° ± 12.8	0.866	0.24	0.04
	Pelvic tilt	16.9° ± 5.7	16.6° ± 5.3	17.1° ± 6.1	0.763	0.94	-0.07
	Tibia shift	5.7° ± 3.3	4.2° ± 2.2	7.1° ± 3.5	0.017**	0.91	-0.95
	Fibula alignment	5.5° ± 3	6.3° ± 3.1	4.8° ± 2.7	0.491	0.94	0.49
	Foot angle	29.8° ± 6	33.7° ± 26.2	26.2° ± 4.2	0.001***	0.93	1.6

*ASIS: anterior superior iliac spines; PSIS: postero superior iliac spines. *p-value < 0.05; **p-value < 0.01; ***p-value< 0.001*

4. Discussion

This study aimed to present normative data about the digital posture evaluation of healthy young adults through the mobile app Apecs and evaluate its reproducibility. The first finding was that the app is sensible to postural variation, considering that it was capable of detecting postural differences between males and females. The second finding of the study was that this mobile app presents a good inter-rater reproducibility for all the postural variables examined except for head alignment, trunk inclination and axillae alignment in the anterior and posterior coronal plane, and acromion alignment in the sagittal plane.

The Apecs app has already been used for research purposes to evaluate postural behaviors related to specific ergonomic studies' work [12] and to evaluate body segment angles in subjects with adolescent idiopathic scoliosis [442]. However, the studies mentioned above had small samples; the first used the app only to compare their sample's posture at rest and during the working activity, and the second only to evaluate angles in the frontal and sagittal plane. Hence, to the best of our knowledge, this is the first study that employs the mobile app Apecs to evaluate global posture, providing normative data and assessing its reproducibility as a posture evaluation tool.

The sample in this study was composed of 100 participants equally distributed between males and Females, and the Apecs mobile app was capable of detecting postural differences when present. It emerged from the postural analysis of the anterior coronal plane that females presented a wider knee angle; this could be due to the overall increased knee laxity and reduced stiffness in females compared to males [443]. In a previous study by Raine et al. [444], no sex differences were found for head inclination on the sagittal plane; conversely, we found that the head inclination was more accentuated in the female group compared to the male group. However, Raine et al's study is dated 1997, and they considered an older sample size. These observations may be the cause of the differences in our study. Iacob et al [190] analyzed the posture of a sample of people with malocclusion through the PostureScreen ® mobile app comparing it with a healthy sample. We found a difference between our postural data gathered with

Apecs and the one reported by Iacob et al for the same variable analyzed. These authors found on the frontal plane a head alignment in their sample of 3.86°± 2.45, a shoulder alignment of 1± 0.97 and a hip deviation of 1.42± 1.28 while for the same variable we report a head alignment of 2.7±1.5, a shoulder alignment of 1.5± 1.2, and postero-superior spines inclination of 1.9°± 1.4. The differences in the postural evaluation between the two app might be due to the differences in the samples considering that the control group of young healthy young adults investigated by Iacob et al was composed only by 14 people and almost exclusively females.

We found a statistically significant difference in the sagittal plane for foot angle, with the male group presenting higher values; this finding could be related to the general bigger size of the foot anthropometrics of males [445]. In the anterior and posterior coronal planes, we did not find any statistically significant difference between gender for foot posture parameters in line with previous studies [446,447].

The reproducibility analysis of Apecs showed excellent results for all the variables examined on the sagittal plane except for the acromion alignment. The marker placed on the acromion was not clearly visible during the positioning of the digital marker in this plane of space, making it difficult to be evaluated with consistency among raters. The same issue occurred in the posterior coronal plane for the trunk inclination, where the app asks to identify "the most intended point of the trunk" which was not easy to replicate for the raters. Interestingly, the two less reliable measures in the anterior coronal plane were the axillae alignment and the trunk inclination, indicating that this mobile app should be carefully considered when a precise measure of these variables is needed. Accordingly, with what was stated by Szucs et al. [188], that evaluated the Posture Screen Mobile® app, we suggest that the quality of the evaluation is higher when markers are placed on the subject and are clearly visible during the positioning of the digital markers; however neither the Apecs manufacturer nor the Posture Screen Mobile one specifies this in their instruction for postural analysis.

The current study presents some limitations. First, we considered a sample composed exclusively by young adults, so we could not assess if the Apecs app could be a feasible tool to employ in the postural evaluation for pediatric and elderly populations. Second, all the individuals in the sample were healthy, thus, these results should be carefully interpreted when compared to individuals with pathologies that influence the musculoskeletal system. Third, we did not compared measures collected with Apecs with postural gold standard instruments to assess the validity of the app. Further studies should investigate about the validity of Apecs as a reliable postural assessment tool, comparing it with rasterstereography or marker-based systems. However, these normative data may help those involved in the analysis of postural alterations as a comparative standard with a healthy sample. Finally, the digital landmarks positioning accomplished with the app may be challenging for less experienced users and might change the evaluation results.

5. Conclusions

The mobile postural app Apecs demonstrated good reproducibility for most of the postural variables analyzed and could detect postural differences between males and females when present. The app was easy to use for all the raters, from the more experienced to the less one, indicating that Apecs could be a cheap and feasible good alternative to more expensive postural assessment devices for researchers and clinicians. However, trunk inclination and axillae alignment were unreliable in all the planes of space where they were evaluated, and head alignment was reliable only in the sagittal plane. Clinicians should be aware of this issue while using Apecs and carefully predetermine the landmarks positioning and digital identification during the analysis, to minimize the possibilities of errors for the postural variables not clearly described by the Apecs' manufacturer. In conclusion, the Apecs app could be a potentially useful tool for clinicians and researchers to implement in the preventive care of postural disorders given its ease of use and cheap costs.

Ergonomic evaluation of young agricultural operators using handle equipment through electromyography and vibrations analysis between the fingers

Federico Roggio [1,2], Ermanno Vitale [3], Veronica Filetti [3], Venerando Rapisarda [3],

Giuseppe Musumeci [1,5], Elio Romano [4]

[1] Department of Biomedical and Biotechnological Sciences, Section of Anatomy, Histology and Movement Science, School of Medicine, University of Catania, Via S. Sofia N° 87, 95123, Catania, Italy

[2] Sport and Exercise Sciences Research Unit, Department of Psychology, Educational Science and Human Movement, University of Palermo, Via Giovanni Pascoli 6, Palermo, 90144, Italy

[3] Department of Clinical and Experimental Medicine, Occupational Medicine, University of Catania, Occupational Medicine; Via Santa Sofia N° 78, 95123 Catania, Italy

[4] Research Centre for Engineering and AgroFood Processing, Council for Agricultural Research and Economics - Via Milano, 43 e 24047 Treviglio (BG), Italy

[5] Research Center on Motor Activities (CRAM), University of Catania, Via S. Sofia N° 97, 95123, Catania, Italy

Safety and Health at Work

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Introduction

Agricultural employment comprises a large portion of the world's workforce, estimating 1.3 billion people involved in this field. However, this job has been recognized as one of the most harmful industries [448]. Agricultural handle equipment (AHE) is present on all production areas' farms. Brushcutters are necessary to control weeds; electric saws and hedge trimmers to redefine the shape of trees, bushes, and hedges. Numerous studies observed the effects of mechanical and physical-chemical methods used for this practice [449-451] to quantify the various risks to which operators are often exposed, such as whole-body vibrations (WBV), hand-arm vibrations (HAV), noise, physical fatigue, improper postures, and exposure to chemicals [452,453]. AHE is easily maneuverable and transportable; however, it can often cause acute traumas such as accidental injuries to the feet or hands, and chronic injuries resulting in weakening the hand nerves or low back pain [454-457]. Hand-arm vibration syndrome (HAVS) is a condition that occurs due to consistent use of vibrating equipment (e.g., brushcutter or electric saw) affecting operators that are continuously exposed to HAV. The distal part of the body, i.e., fingers and hand, absorb the vibrations, causing HAVS's vascular and sensorineural symptoms [458]. The vibrations reach then the arm and the shoulder, affecting the sensorineural component leading to pain and partial hand loss of functions [458].

Work-related musculoskeletal disorders are the most disabling condition among agricultural operators [459], whereas repetitive movements, long hours of activities, awkward working posture, or WBV lead to chronic pain. Over time repeated use of portable equipment can predispose operators to pain in wrists, hands, shoulder, and neck, as found in 92% of a population of Spanish agricultural workers [460]. The usual working posture places a significant physical demand on the body, especially the back, doubling the risk of lower back pain than the general working population [461]. Several studies analyzed the use of professional brushcutters, highlighting the increased risk of developing HAVS, including circulatory, sensory, and manual disorders [462-465].

The surface electromyography (sEMG) and the digital postural analysis can measure the adverse effects of the AHE vibrations on the body and the posture alterations arising from its incorrect use during the daily working time. This study aimed to observe the response capacity of surface electromyography deriving from three different agricultural portable equipment in different static and dynamic conditions. Furthermore, we analyzed the altered postures and the trunk stress to understand any complementarity between the prolonged use of these tools and the musculoskeletal pain onset.

Materials and methods

Twenty male young agricultural operators were recruited at the Occupational Medicine clinics, University of Catania. The mean age of our sample was 24 ± 1.54 years, mean weight 75 ± 2.76 kg, mean height 176.13 ± 6.01 cm, with an experience of 4.3 ± 1.49 years in the field of agriculture, all right-side dominant. The exclusion criteria were: recent traumas to the upper limbs, neurodegenerative or musculoskeletal diseases, and heart diseases. Portable surface electromyography evaluated the muscles' activity while holding AHE. The data collection was approved by the Research Center in Motor Activities (CRAM), University of Catania (protocol n.: CRAM-016-2020, 16/03/2020), in accordance with the Declaration of Helsinki. Prior to testing, all participants provided written informed consent. The participants were instructed to perform four different measurements while holding an AHE: static with the engine off; static at minimum engine speed; static at maximum engine speed; dynamic with repeated gestures in a vertical and horizontal direction (simulating the cutting gesture).

The most common tools used in gardening, i.e., monobloc brushcutter, electric saw, and electric hedge trimmer were used as AHE to test their vibrations over the upper arms. The monobloc brushcutter (Fig. 1a) had a nominal power of 0.8 kW and a weight of 5.6 kg, consisting of the motor, a tubular metal rod within which the transmission shaft rotates, and the rotating tool. The electric saw (Fig. 1b) had a cutting bar length of 40 cm, a rated power of 1.6 kW, and a weight of 3.9 kg. The electric hedge trimmer (Fig. 1c) was equipped with a double-action blade 50 cm long, with a distance between the teeth of 16 mm, had a nominal power of 0.58 kW, and a weight of 4.1 kg.

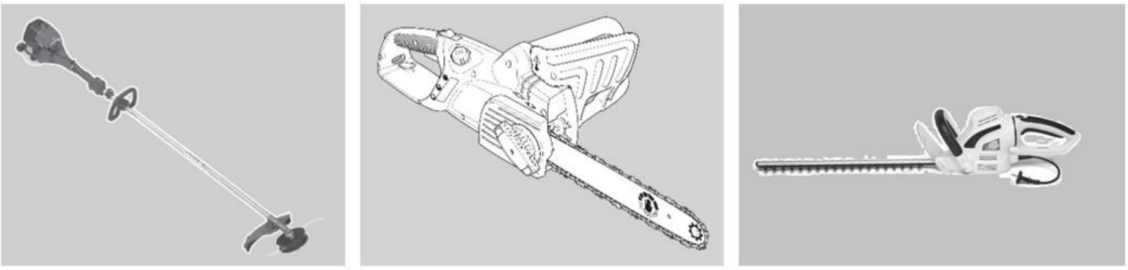


Fig 1: *Agricultural handle equipment. (a) brushcutter, (b) electric saw, (c) hedge trimmer.*

Four portable and lightweight sEMG data loggers with an internal lithium-ion battery (OT Bioelectronics, Italy) were placed on the forearms and shoulders. All sEMG signals were sampled at a frequency of 800 Hz; then amplified and filtered. Two pairs of adhesive circular surface electrodes were applied with a diameter of 24 mm and a 15 cm cable together with the reference electrode as indicated by the manufacturer [466]. The electrodes were positioned over the neck area, i.e., transverse fibers of trapezius, rhomboids major and minor, levator scapulae, and in the inner part of the forearm, i.e., flexor digitorum superficialis, flexor pollicis longus (Fig. 2), according to occupational medicine guidelines [467]. The data collected were processed to extract the mean frequency (MNF), a fatigue index based on observing the frequency of the surface electromyographic signal [468-470], i.e., myoelectric signal and conduction velocity alterations of the examined muscles during the dynamic exercise proposed in the experiment [471].

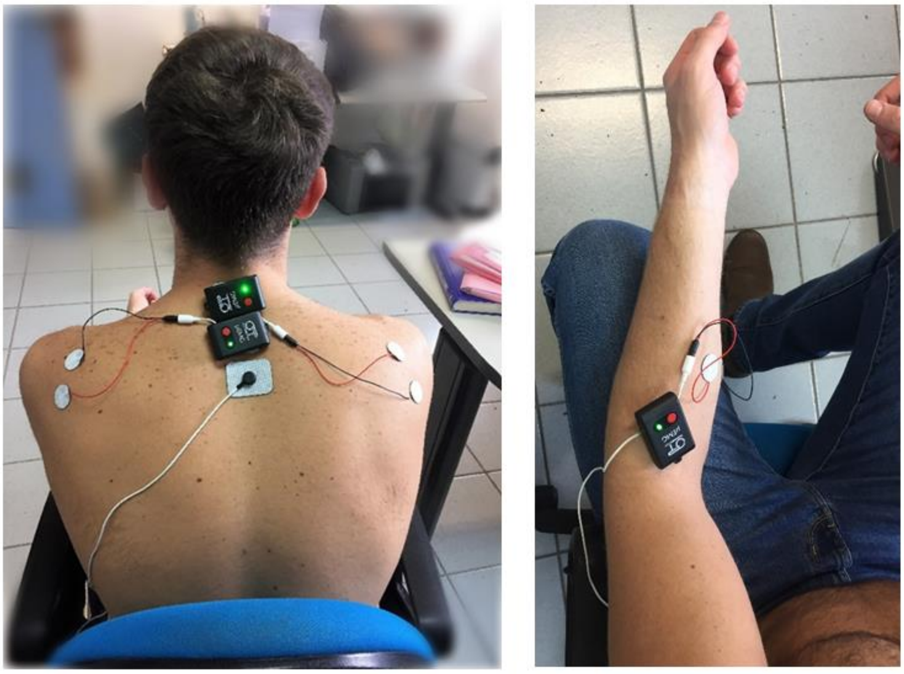


Fig 2: *sEMG application over the neck and shoulders (a), and the forearm (b).*

The AHE's vibrations flowing through the handle were collected with a triaxial accelerometer hand/arm (10mV/G) weighing 4 grams, according to the indication of UNI EN ISO 5349-1, placed on a unique handle (Fig. 3) between two fingers, as suggested by Peterson et al. [472]. Only the vibrations of the holding hand were collected for the experiment. The collection frequency was 24.5 Hz, as proposed by Seman et al. [473]. The elaboration process consisted of extracting the central area of the acquisition and calculating the root mean square value (RMS) of the frequency weighted acceleration, expressed in ms^{-2}.

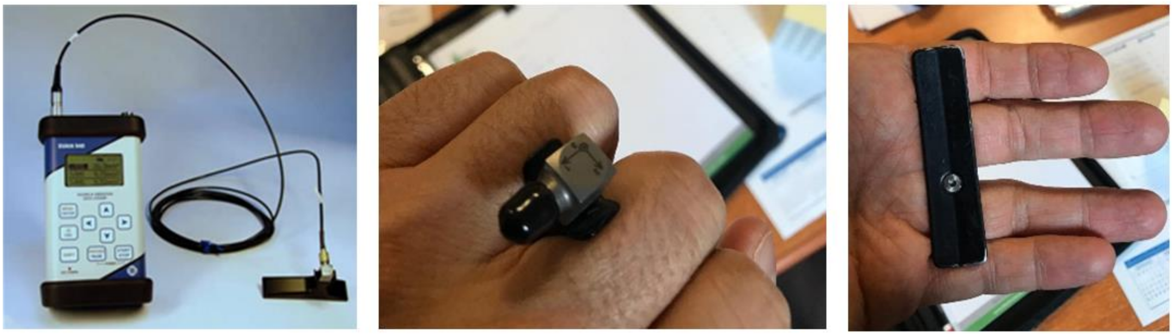


Fig 3: *The analyzer used to collect the vibrations (a) made of an accelerometer (b) and an handle equipment (c) to hold the accelerometer.*

The postural assessment has been carried out through a digital tablet application, APECS mobile app (New Body Technology SAS, Grenoble, France), able to reconstruct the posture from photography [29]. We placed adhesive markers over the anatomical landmarks, and then, after the photography, we conducted the digital marker placement to analyze the whole body posture as reported in Fig. 4. Furthermore, we analyzed the working posture, i.e., trunk inclination (TI), leg – hip – shoulder complex (LHS), Fig. 5. We analyzed the TI by measuring the angle between a line passing through the C7 process and the posterior superior iliac spine and a straight line passing through the same points. For the analysis of LSH complex we placed the markers at the lateral malleolus, greater trochanter and humeral greater tuberosity.

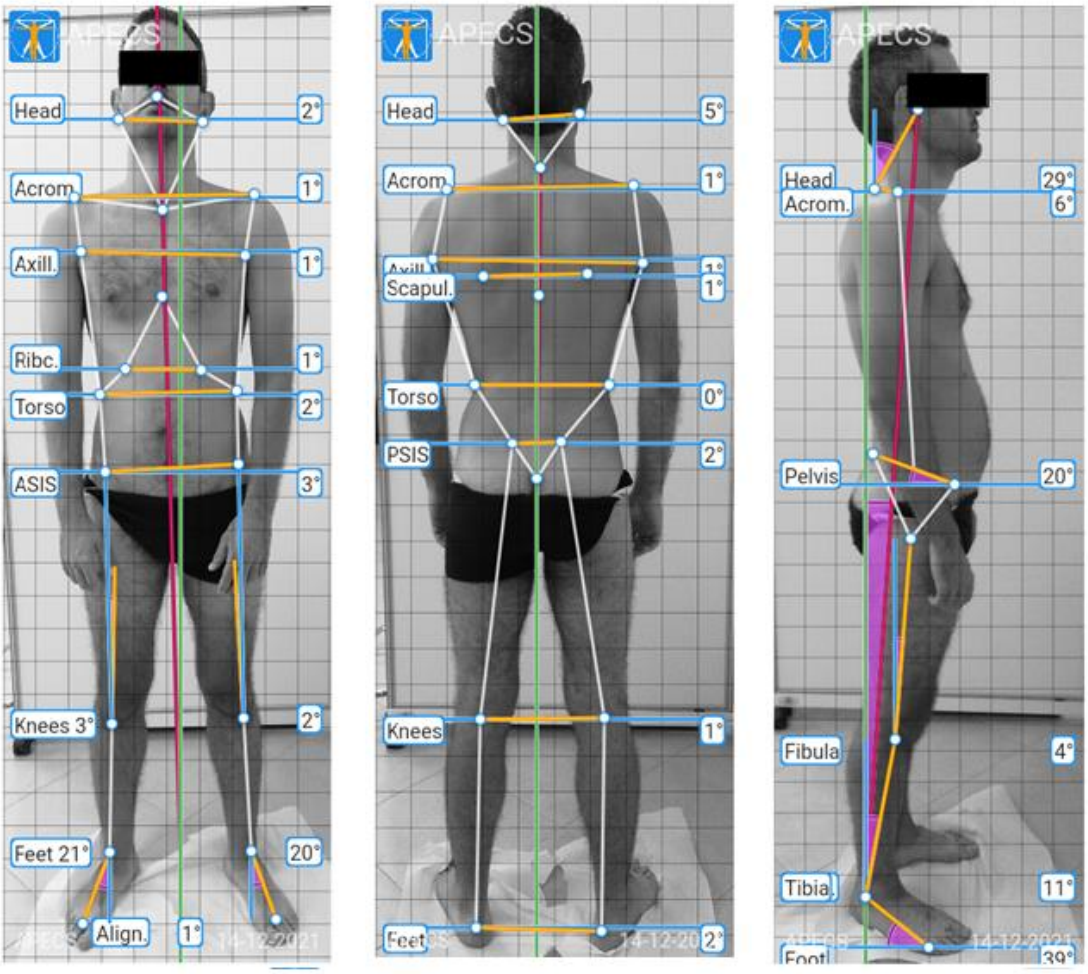


Fig 4: *Digital postural analysis in frontal (a), posterior (b) and sagittal (c) planes. The white points indicate the anatomical landmarks examined for the postural assessment. The yellow lines indicate the symmetry evaluation between the two sides of the same anatomical landmark. The green line indicates the perpendicular of the body. In figure (a) the red line indicates the lateral shift of the body. In figure (c) the fuchsia zones indicate the angular variation to the axis.*

Fig 5: *Explanatory image of the postural analysis of the working posture in the upright position (a), slightly forward inclined (b), and excessive forward inclination (c).*

Data analysis

Statistical analysis was performed using R Project for Statistical Computing (Vienna, Austria). The data have been processed through descriptive and inferential analysis. The Shapiro-Wilk test verified the normality distribution; the Breusch-Pagan Test verified the homogeneity of the variance. The analysis of variance (ANOVA) was applied to test the differences among the different agricultural equipment in static or dynamic conditions. A post hoc test, the Duncan test, measured specific differences between pairs of means (p-value <0.01). The dependent variables were the MNF representing electromyography and the RMS for vibrations. The independent variables were: the different AHE used, the test conditions (static or dynamic), the direction of the movements (vertical or horizontal), the body segments. Mean, and SD were used to analyze the data of the digital postural analysis.

Results

The highest MNF and RMS values were observed under the dynamic conditions of all three AHE involved in the study. The brushcutter's electromyography showed high values even in the static condition with the engine at maximum speed. Meanwhile, the RMS values of the static conditions of the saw and hedge trimmer showed values close to those obtained under dynamic conditions. Table 1 reports the maximum values recorded, mean value, and standard deviation.

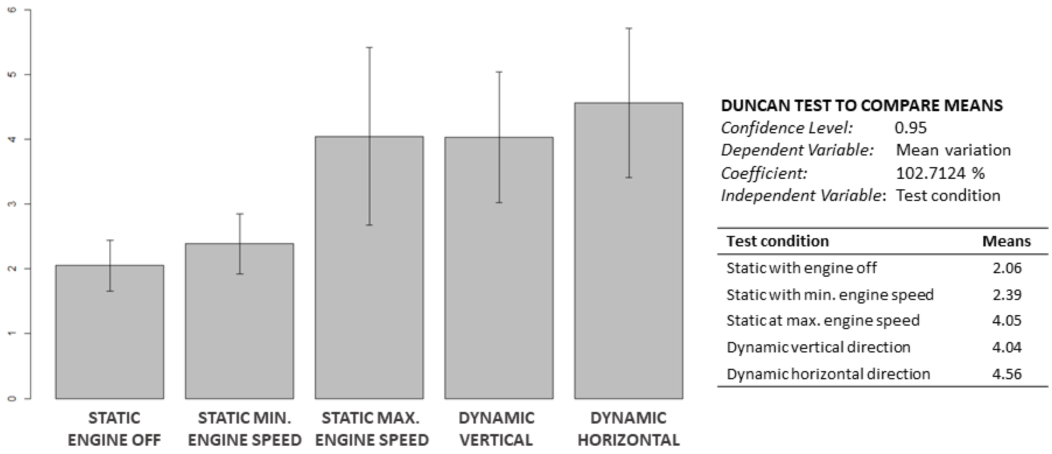
Table 1. Results of electromyographic and vibrational tests in different conditions referred to the shoulder holding the AHE

AHE	TEST CONDITION	MNF (Hz)			RMS (ms^{-2})		
		MAX	MEAN (SD)		MAX	MEAN (SD)	
Brushcutter	*Static engine off*	8,75	2,07	(0,42)			
	Static min engine speed	9,52	2,30	(0,37)	5,91	5,61	(0,18)
	Static max engine speed	14,99	4,04	(0,72)	6,38	6,25	(0,12)
	Dynamic horizontal	15,50	5,54	(0,95)	9,26	9,13	(0,11)
Electric saw	*Static engine off*	8,47	2,20	(0,44)			
	Static min engine speed	9,55	2,45	(0,50)	2,79	2,60	(0,20)
	Dynamic vertical	12,54	3,41	(0,60)	3,09	2,92	(0,12)
Hedge trimmer	*Static engine off*	6,94	1,88	(0,33)			
	Static min engine speed	9,40	2,40	(0,49)	5,04	4,88	(0,11)
	Dynamic vertical	20,22	4,64	(0,99)	5,16	4,99	(0,08)
	Dynamic horizontal	16,64	3,80	(0,82)	5,25	5,08	(0,11)

MNF: mean frequency; RMS: root mean square; AHE: portable agricultural equipment

The analysis of variance showed that the values of MNF for electromyography of the right shoulder and RMS for vibrations had a normal distribution with homogeneity between the variances. The ANOVA on the MNF values revealed a no variability between operators (p-value> 0.05). On the contrary, a statistical difference (p-value < 0.01) of the MNF was found between the brushcutter, electric saw, and hedge trimmer; between the four different test conditions (static, dynamic, engine on and off); and between the right and left side of the body. The ANOVA conducted on RMS values revealed a significant influence between the static or dynamic conditions (p-value <0.01).

The Duncan test (Fig. 6) showed a statistical difference between the different test conditions (static with engine off, static at min engine speed, static at max engine speed, dynamic in vertical and horizontal movements), with mean MNF values of approximately double at maximum engine rpm. Among the AHE of the study (Fig. 7), the brushcutter showed the highest mean MNF value (3.37 ± 0.38 Hz), the hedge trimmer (3.18 ± 0.42 Hz), and the saw (2.68 ± 0.51 Hz).



DUNCAN TEST TO COMPARE MEANS

Confidence Level: 0.95
Dependent Variable: Mean variation
Coefficient: 102.7124 %
Independent Variable: Test condition

Test condition	Means
Static with engine off	2.06
Static with min. engine speed	2.39
Static at max. engine speed	4.05
Dynamic vertical direction	4.04
Dynamic horizontal direction	4.56

Fig 6: *Duncan Test to compare means of the different test conditions*

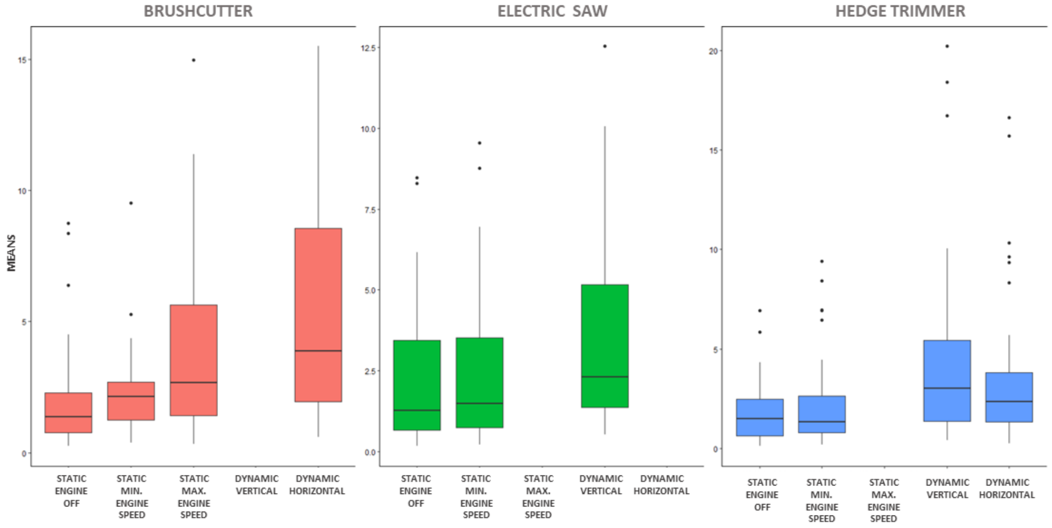


Fig 7: *Boxplot to compare means of each AHE in the different test conditions*

The mean RMS values were statistically different (p-value <0.01) with higher values for the brushcutter (5.25 ± 1.24 ms^{-2}), then the hedge trimmer (3.74 ± 0.65 ms^{-2}), and the saw (1.84 ± 0.12 ms^{-2}). The test conditions were also statistically different from each other (p-value> 0.01). Horizontal movements had the highest mean value (7.10 ± 1.75 ms^{-2}), then the static test with the engine at the maximum rpm (6.24 ± 1.08 ms^{-2}), the static test at minimum rpm (4.37 ± 1.02 ms^{-2}), and finally the vertical movements showed the lower mean value (3.95 ± 0.48 ms^{-2}). Mean MNF differences were significant between the right (1.99 ± 0.04 Hz) and left (4.00 ± 0.12 Hz) part of the body, between both forearms (4.72 ± 1.09 Hz) and both shoulders (1.8 ± 0.37 Hz). The correlation between electromyography and vibrations (Fig. 8) was significant for more than 60%. The tests showed higher MNF values corresponding to higher AHE accelerations (Fig. 9).

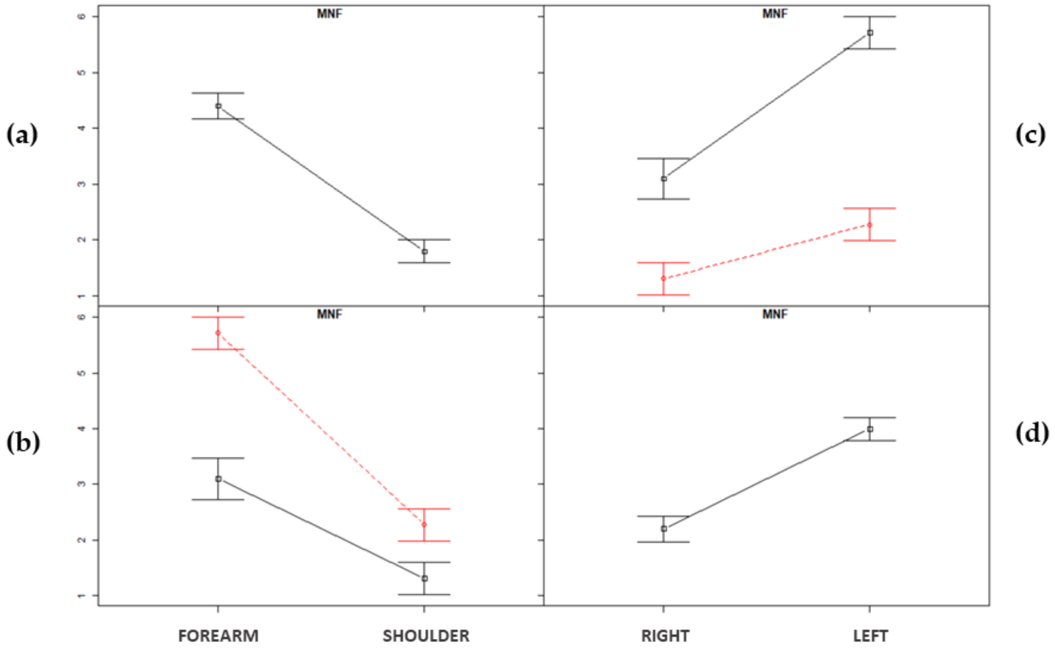


Fig 8: *Average MNF in the two observed body regions (forearms and shoulders) distinguished between right and left.*

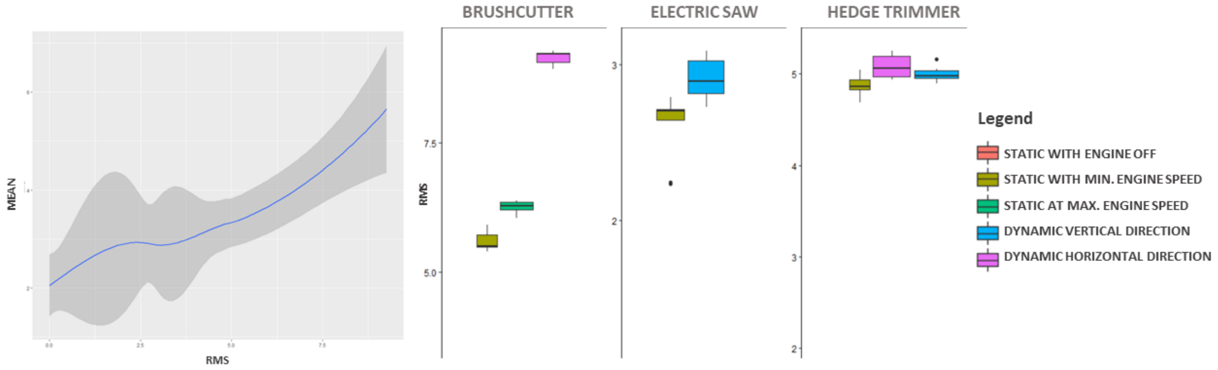


Fig 9: *A line plot to compare MEAN with RMS (a) the gray area indicates the confidence interval based on the SD. RMS boxplot of the different AHE (b).*

The digital postural assessment showed an asymmetry of the main arm involving the respective side of the trunk. As reported in Table 2, there is a general asymmetry of the main anatomical landmarks presenting a constant misalignment bending on the right side. The frontal and back sides data indicate a general lean toward the right side; the data of the sagittal plane indicate a forward lean. The segments reporting a relevant difference are: head right inclined in the anterior frontal plane (5.7° ± 1.2°); the right scapula lower than the right in the posterior frontal plane (8.5° ± 1.8°); the head forward-shifted in the sagittal plane (37.6° ± 10.9°). Furthermore, the trunk inclination and the leg-hip-shoulder angle of the working posture indicate a TI = 34.15° ± 5.7° and LHS = 136.8° ± 6.9°.

Table 2. Results of digital postural analysis

BODY PLANE	BODY SEGMENT	MEAN	SD
Anterior frontal	*Body alignment*	1.4° R	0.46
	Head	5.7° R	1.23
	Acromion	3.3° R	1.03
	ASIS	1.8° R	0.70
Posterior frontal	*Shoulders*	3.2° R	0.90
	Scapulae	8.5° R	1.80
	PSIS	8.1° R	1.67
Sagittal	*Body alignment*	4.4° F	1.27
	Head	37.6° F	10.9
	Acromion	7.1° F	3.10
	Pelvis	11.5° F	4.80
	Femoris	8.1° F	2.60
	Fibula	8.5° F	2.49

ASIS: anterior superior iliac spine; PSIS: posterior superior iliac spine; R= right-shifted; F: forward-shifted

Discussion

Agricultural operators are often subjected to harmful conditions that expose the body to discomfort and awkward postures. The vibrations deriving from prolonged use of AHE can predispose the upper arms to joint inflammation. Additionally, assuming the wrong posture repeated over time overburdens the trunk, causing low back pain or disc degeneration. Based on these conditions, we investigated the interaction between the AHE's vibrations and working postures on agricultural operators. Prolonged and excessive WBV or HAV are associated with various occupational health disorders, mainly concerning hands, arms, and spine [474,475]. Our results showed that the brushcutter is the AHE that induces higher stress in sEMG activity and vibration stress. It presents the higher sEMG value during the horizontal movements, probably because it requires a greater muscle force to move it due to its length. Furthermore, it produces the higher vibrations stress value during these conditions. Then follows the hedge trimmer, with the higher sEMG activity during the vertical movements, presenting the higher vibrations during the horizontal movements. Finally, the electric saw is the AHE inducing less sEMG activity and vibration stress attesting to its higher values only during the horizontal movements. All the AHE considered produce higher values during the movements, which is the most alarming condition since agricultural operators actively use these tools. WBV can cause muscle inflammation and microtrauma of the spine, conditioning the biodynamic response to vibrations. Tian et al. [354] analyzed the prevalence of degenerative lumbar osteoarthritis in 3859 Chinese adults; they reported that WBV is a predominant risk factor in developing spine osteoarthritis (OR 2.21, 95% CI 1.51-3.23). The increased risk of developing low back pain due to WBV has also been investigated among farmers, assessing an OR of 2.44 (95% CI 0.95-6.43) [476]. Vihlborg et al. [477] observed that exposure to HAV increases the risk of carpal tunnel syndrome with an OR of 1.61 (95% CI 1.46-1.77), and this risk increases for every mean year exposure of 2.5 ms^{-2} with an OR of 1.84 (95% CI 1.38-2.46). They conducted these analyses in men <30 years of age, as we did. It corroborates our idea that the HAVS occurs when operators are young, but they cannot feel the harmful effect of vibration because the body hides them. This mechanism predisposes young operators to encounter chronic pathologies in old age [350,478,479]. An anti-vibration handle could be used to mitigate the adverse effects of WBV or HAV. They can reduce vibrations by about 60%, keeping the vibrations within the exposure limit values defined by the European Union [480]. Another method could be using vibration-reducing gloves which substantially reduce the vibrations transmitted to the palm, hand dorsum, and wrist [481].

We detected several differences between the right and left arm, observing a general lower sEMG activity for the right arm. The sample was all right-side dominant, which explains this side's reduced sEMG activity. However, this condition can alter the balance of the body. The digital posture analysis highlighted an altered posture due to awkward working positions. All participants had the right side lower than the left, specifically the shoulder, scapula, and elbow; furthermore, the head was right tilted. The right anatomical landmarks lowered may be a work-induced side effect; however, the effects of weight-bearing asymmetry may lead to postural instability and increase the contralateral's compensatory activity [482]. The operators constantly keep an awkward posture, whereas the left side is kept higher to compensate for the overburden of the right side. Repeated over time, it establishes a definitive paramorphism that leads early to sporadic pains, lately to musculoskeletal disorders, i.e., low back pain or disc herniation. The sagittal trunk inclination of 34.15° ± 5.7° highlights a risky condition. Different authors analyzed the association between trunk inclination and LBP, assessing the risk of developing it when working with a trunk flexion greater than 60°. Punnett et al. [483] classified the trunk inclination into three categories: "normal" equal to 20°, "mild" from 20° to 41°, and "severe" when exceeding 45°. The risk to develop LBP is four times higher (OR 4.2, p-value = 0.014) for those working at least 10% of the working time (8 hours) in mild trunk flexion, and six times higher for those working more than the 10% of the working time in mild trunk flexion (OR 6.1, p-value = 0.014). Hoogendoorn et al. [484] found that exceeding 10% of the working time with the trunk flexed more than 30° can increase the risk of developing LBP (RR 1.19, 95% CI 0.86–1.65). Meanwhile, Coenen et al. [485] observed that exceeding 5% of the working time with the trunk flexed more than 60° has a higher risk of developing LBP (OR 2.35, 95% CI 1.46-3.79).

The predisposition to musculoskeletal disorders due to work-related conditions is a red flag that the Ministry of Labour has to consider. Industrial policies and rural development strategies should offer innovative solutions since operators are unaware of the potential risks of their job. For instance, in Italy, the incidence of injuries in the agricultural sector is significant—targeted interventions should be addressed and implemented [486]. Educational and training models could support the operators, such as: specialized courses, learning of risk analysis and accident prevention, increase in workplace safety checks, financial support in the purchase of more advanced products, or dissemination of the communications promoting awareness to job accidents.

Conclusions

Vibrations of agricultural handle equipment and awkward working postures represent a risk that increases occupational illness, injuries, and chronic diseases among agricultural operators. We investigated these interactions by analyzing the sEMG activity of arm and trunk muscles using three agricultural handle equipment, i.e., monobloc brushcutter, an electric saw, and electric hedge trimmer, and the postural alterations present among a young group of agricultural operators. The results highlight that the prolonged vibration exposure and constantly awkward posture can predispose the operators to suffer from hand-arm vibration syndrome and neck and low back pain. The brushcutter is the handle equipment determining the higher muscle activity and vibration from the hands to the spine. Furthermore, the more evident postural alterations are: head right inclined and forward shifted asymmetry of the scapulae and an increased trunk inclination during the working posture. Young operators exposed to these risks mean adults with undeniable musculoskeletal pathologies. Preventive measures are required, i.e., anti-vibration handle to mitigate the adverse effects of vibrations, educational and training models to prevent incorrect postures while working.

Exploiting Real-World Data To Monitor Physical Activity In Patients With Osteoarthritis: The Opportunity Of Digital Epidemiology

Silvia Ravalli[1], Federico Roggio [1,2,], Giovanni Lauretta[1], Grazia Maugeri[1], Michelino Di Rosa[1] and Giuseppe Musumeci[1,3,4]

[1]Department of Biomedical and Biotechnological Sciences, Human Anatomy and Histology Section, School of Medicine, University of Catania, Via S. Sofia 87, 95123 Catania, Italy

[2]Department of Psychology, Educational Science and Human Movement, University of Palermo, Via Giovanni Pascoli 6, 90144 Palermo, Italy

[3]Research Center on Motor Activities (CRAM), University of Catania, 95123 Catania, Italy

[4]Department of Biology, College of Science and Technology, Temple University, Philadelphia, PA 19122, USA

Heliyon

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Introduction

Evidence-based data tie physical inactivity and sedentary habits to non-communicable diseases, including diabetes, cardiovascular disorders, and obesity [487,488]. Exercising is widely suggested as a valuable preventive strategy to avoid the onset and slow down the progression of several pathologies. The American College of Sports Medicine (ACSM) and the World Health Organization (WHO) recommend exercising at least 30–45 min every day to a total of 150–300 min per week [489-491]. Osteoarthritis (OA), is a degenerative disease of the articular cartilage that mainly affects older people, causing disability worldwide [492]. Current treatments include the use of non-steroidal anti-inflammatory drugs, opioid and non-opioid analgesics, intra-articular injections of steroids and hyaluronic acid, and surgical procedures [493]. However, side effects and contraindications of these treatments suggest considering adopting new non-pharmacological, regenerative, and behavioral approaches [494,495]. Physical activity (PA) represents a low-cost and feasible strategy to preserve joint function, flexibility, decrease pain and fatigue, and improve balance and muscle strength [496]. Patients with OA are strongly recommended to be physically active, avoiding excessive load or strenuous training [494,495]. Especially in the case of knee OA, the amount of activity performed by the lower limb influences the muscle strength and lubrication of the joint capsule, which can lead to experiencing pain and pathological dysfunctionality [162,327,497]. Underestimation of OA symptoms is common, especially in young subjects. Joint pain can often be traced to poor posture, trauma, or aging. For this reason, treatments such as exercise and physical therapy are neglected rather than strictly adopted. Patients with OA are advised to join exercise programs, although involvement is often very low. Maintaining awareness of the severe consequences of inactivity and the benefit of exercise is essential, especially in the presence of a musculoskeletal disorder.

Human Activity Recognition (HAR) is a scientific approach aiming to collect data from various human activities such as walking, running, sitting, driving, and other daily activities [498]. Inertial measurement systems and wearables, such as smartphones or smartwatches, embedded with a 3-axial accelerometer and 3-axial gyroscope sensors are suitable for this use. The availability of digital devices with integrated sensors has sparked a growing interest in their use in health care systems and sports science [499,500]. This approach strengthens the ability to recognize human activities in controlled and uncontrolled environments differently from biomechanics laboratories, which can only perform these measurements in controlled settings. Several wearable devices on the market are valid for monitoring human physical health [501]. The smartwatch market has grown exponentially in recent years. Sales of these devices were approximately 9 million in 2016, 12 million in 2017, reaching 22.6 million smartwatches sold in the United States during 2020 [502]. The high rise in sales of wearable devices reflects the interest in tracking everyday activities in consumers' lives [502]. The automatic recognition of PA practice and the monitoring of daily gestures through digital devices produce measurements that have been associated with the health status of several pathologies and have provided suggestions for their management [503]. Wearable devices can monitor PA in clinical practice and scientific research, especially for a prolonged period, revealing unpredictable changes in the investigated population [504].

This review aims at highlighting recent relevant literature about the use of digital devices for monitoring levels of PA in patients with OA, discuss the harness of real-world data deriving from digital devices in the context of digital epidemiology, and provide recommendations for researchers and clinicians approaching the use of wearables to collect health-data.

Wearables To Analyze Physical Activity In Osteoarthritic Patients

Physical activity is defined as any movement produced by the muscles that expend energy, but it can include moving during leisure time or running at 15 km/h. The suitability and affordable cost of the wearables can improve health analysis in both daily activities and sports practice conditions thanks to the prolonged data collection. Patients with musculoskeletal diseases such as low back pain, osteoarthritis, and rheumatic inflammatory diseases are not well predisposed to the practice of PA [505], although it is considered indispensable to reduce pain and hypo-functionality [506].

Farr et al. [507] conducted one of the first studies about using wearables for a prolonged time in patients with OA. They attached an accelerometer through a belt to the right hip and measured the time spent in moderate, vigorous, and moderate-to-vigorous. Only 30% of the examined group (255 patients) achieved the CDC/ACSM recommendations [508,509]. The PA average minutes were moderate 23.6 ± 17.2 mins, vigorous 0.95 ± 3.5 mins, and moderate-to-vigorous 24.54 ± 19.1 mins. These results reflected a critical scenario among OA patients since a small percentage achieved a minimum of 30 minutes/day of moderate to vigorous PA.

A prospective study conducted by Morcos et al. [510] recruited 122 patients with hip OA scheduled for total hip arthroplasty, observed a positive correlation between PA levels and UCLA Activity score, Western Ontario and McMaster Universities Arthritis Index (WOMAC), Pain Catastrophizing Scale (PCS), Short-Form Health Survey (SF-12) and Harris Hip Scale (HHS). All patients wore a wristband activity tracker, Fitbit, for 24/7 consecutive days prior to their scheduled surgery. The results showed, moreover, that the mean number of steps per day was 5721 ± 3920. In line with the criteria by Tudor-Lock [511,512], which classifies as sedentary those who accomplish less than 5000 steps per day, 51% of the participants would be considered sedentary. According to their results, measuring the PA levels can predict functional recovery after total hip arthroplasty, making wearables valuable tools for healthcare professionals.

The psychosocial aspects can benefit from digital supports because the patients feel more involved in the surgical/rehabilitation program. Long times and delays in functional recovery often arise from a lack of communication with the doctor or the fear of pain. These devices can improve trust, reduce recovery times and enhance the cooperation between doctor and patient, whereas they are monitored during daily life. In terms of adherence, the OA patients can accept to wear a device, allowing an objective assessment of PA during everyday activities.

Smartwatch Applications To Monitor Osteoarthritic Patients

Two research groups analyzed the feasibility and acceptability of smartwatches by utilizing two different applications (apps), KOALAP [513] and ROAMM [514-516], among knee OA patients. These two apps send, during the day, a survey to the consumer to evaluate the presence of pain, fatigue, falls, and activities practiced. Furthermore, the accelerometer counts daily steps as common smartwatches. These apps communicate with a specific online server, providing a reliable approach to remote personal health monitoring when worn.

Mardini et al. [517], analyzed the effectiveness of ROAMM (Real-time Online Activity and Mobility Monitor) data from 19 participants for 15 days classified in low and high OA pain groups. During the daily activities, the participants were surveyed in a random time window. The internet connection provided the data collection in real-time while the GPS recorded their location every 15 minutes to elaborate their travel pattern. The results showed a pain intensity range of 0 to 8 (highest reported value) and a valuable difference in GPS records between high and low pain groups. Pain intensity was significantly associated with the traveled area, reporting that each point of increase in mean pain intensity was associated with a decrease in the area walked by 3.06 km. The analysis of GPS data, along with pain intensity, can provide a suitable approach to understand the behavior of individuals and, therefore, suggest the best and personalized healthcare approach to use.

Beukenhorst et al. [513] employed the KOALAP (Knee OsteoArthritis: Linking Activity and Pain) app to study the daily activities of 26 participants for 90 days. The system was set up to trigger 4-5 questions about knee pain and quality of life. Unlike the previous study, these questions were administered within a specific time window, with a response time of 10 seconds per question, and the raw data were collected once the smartwatch was placed in charge. A baseline and follow-up questionnaire were administered about participants' experience with wearables and the relationship with knee OA. Participants wore the smartwatch 73% (81/90) of the days, for average daily usage of 11 hours. The authors focused on psychosocial adherence to the program to discriminate the effectiveness of this approach. Patients found it interesting to learn more about the relationship between pain and activity. They showed high adherence to daily surveys, suggesting that pain questions could be collected more frequently to provide a detailed pain history. However, administering the survey within a specific time frame was reported to interfere with daily activities.

Psychological involvement may be crucial to increase the interest of patients in their health. Firstly, a patient may be afraid to walk because of pain onset. The smartwatch can measure the distance travelled to make the patient aware of the exact moment in which the pain occurs. Secondly, the patient could show higher adherence to the project when he/she feels constantly monitored, especially when there are no expectations. On the contrary, those with high expectations may become skeptical when the pain occurs in different circumstances aside from walking, e.g., sitting or standing.

The Use Of Wearables To Increase Physical Activity Levels

The lack of knowledge of physical activity as healthy support can negatively influence the initiation and perpetuation of its practice. In this scenario, Davergne et al. [517] evaluated through a meta-analysis the efficacy of wearable devices to increase PA behavior in patients with rheumatic and musculoskeletal diseases. They included studies that used both common wearables (pedometer) and advanced wearables (smartwatch, fitness-tracker) for a short period, 0-8 weeks, or long period, > 8 weeks. Participants wearing the devices demonstrated greater adherence to training plans versus control groups; for example, they increased their daily steps for an average of 1,520 steps and achieved 16 minutes of moderate-to-vigorous PA. Those patients increased their fitness levels because they recognized the smartwatch as helpful in analyzing progress or any conditions that could lead to the onset of pain. Patients with OA are generally used to performing about 10 minutes of vigorous activity [518]; instead, these results suggest the efficacy of wearables to motivate patients to increase their PA levels.

Li et al. [519] enrolled 51 participants with knee OA and evaluated the results of a 12-week PA program through a smartwatch and accelerometer, Fitbit, and SenseWear Mini, respectively. During weeks 1-8, a personal trainer followed the participants and helped them with a phone call to change their PA where necessary. During weeks 9-12, participants had to continue their activity without a call from the personal trainer, although they could still email him to ask questions. Data present an increase of moderate-to-vigorous PA from baseline to week 13 of 10 minutes. Patients underwent successive follow-ups, attesting a constant increase of PA levels. In this scenario, wearables to monitor and personal trainer counseling resulted in effective support and motivated the patients to exercise and maintain a more active lifestyle.

Digital Epidemiology

The spread of the Internet and the use of digital devices, e.g., smartphones and wearables, are rapidly introducing a new methodological approach for studying real-world phenomena. Clinical practice is experiencing an escalating transition from manual to automatized data collection. Therefore, as clinical information is progressively stored digitally, manipulating the data is easier and more accessible to other professionals. Collecting data from popular devices allows reaching an enormous number of people. It paves the way for the concept of "Digital Epidemiology" broadly and quickly defined as the epidemiology that uses digital data. Marcel Salathé, currently an associate professor at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, suggests another well-thought definition: "Digital Epidemiology is epidemiology that uses data that was generated outside the public health system, i.e., with data that was not generated with the primary purpose of doing epidemiology" [520]. This definition cleverly focuses on a creative way to analyze existing data, whether normally generated through the daily use of digital devices (e.g., posts on social media, geotracking) or for other purposes (e.g., apps for exercise or consumption of calories, electronic medical and pharmaceutical records). It allows seeking and recognizing those types of data generated outside of public health that may be available and suitable for epidemiological studies, laying the foundation for "worldwide-based cohort studies".

Traditional medical records and self-reported questionnaires regarding the health status of the patients can be corroborated by digital patient-derived data to provide a more comprehensive picture of the clinical case [521] (Figure 1). As wearable for PA in OA subjects, digital sources, practical to retrieve relevant information from the patient, could also be represented by internet activity (social media, forums) [522], credit card payments (pharmacy and grocery purchases), dedicated mobile apps (fitness, mental state, sleep monitoring). Lippi et al. [523] estimated a great increase, in the next future, of the amount of digital epidemiological research, in the form of PubMed articles, based on Google Trends (i.e., the frequency of word research) such as official cancer statistics [524]. Park et al. [525] reviewed 109 research articles that used digital data for epidemiological purposes by identifying health topic domains combined with different data sources. Health professionals can use digital supplementing data to elaborate a well-suited treatment to handle specific disease symptomatology, progression, or therapy outcomes. Instead, the scientific community can observe the influence of different behaviors or risk factors among large populations. In this context, sedentary behavior is one of the risk factors for OA onset, although it is challenging to estimate and quantify during someone's lifetime, exclusively through routine clinical visits and questionnaires. A retrospective investigation through digital data would be a helpful asset to the diagnostic process. Researchers can use sensors, accelerometers, and gyroscopes for longitudinal studies concerning the physical ability and PA of the patient during the day, especially in pathological conditions, such as OA, affecting the musculoskeletal system. Although this method of investigation is still in its infancy, it can spread over different medical areas such as neurodegenerative, psychiatric, or metabolic disorders [526,527].

The intensity, duration, type, and frequency of PA, even simply walking, can draw attention to a wide range of health behavioral patterns, connected to mood changes or sleep disturbances. However, analyzing large-scale datasets requires data and medical science expertise to answer epidemiological questions about health issues. Hicks et al. [528] provided valuable guidelines for harnessing a large volume of data from smartphone apps and wearable devices relating to PA and other health behaviors and addressing the limitations concerning the analysis methods (Figure 2). The authors also outlined several common potential sources of error: complex intrinsic nature of the data because collected without a specific aim; missing data owing to measurement inaccuracy; different expectations about data-sharing partnerships between Academia and Industry.

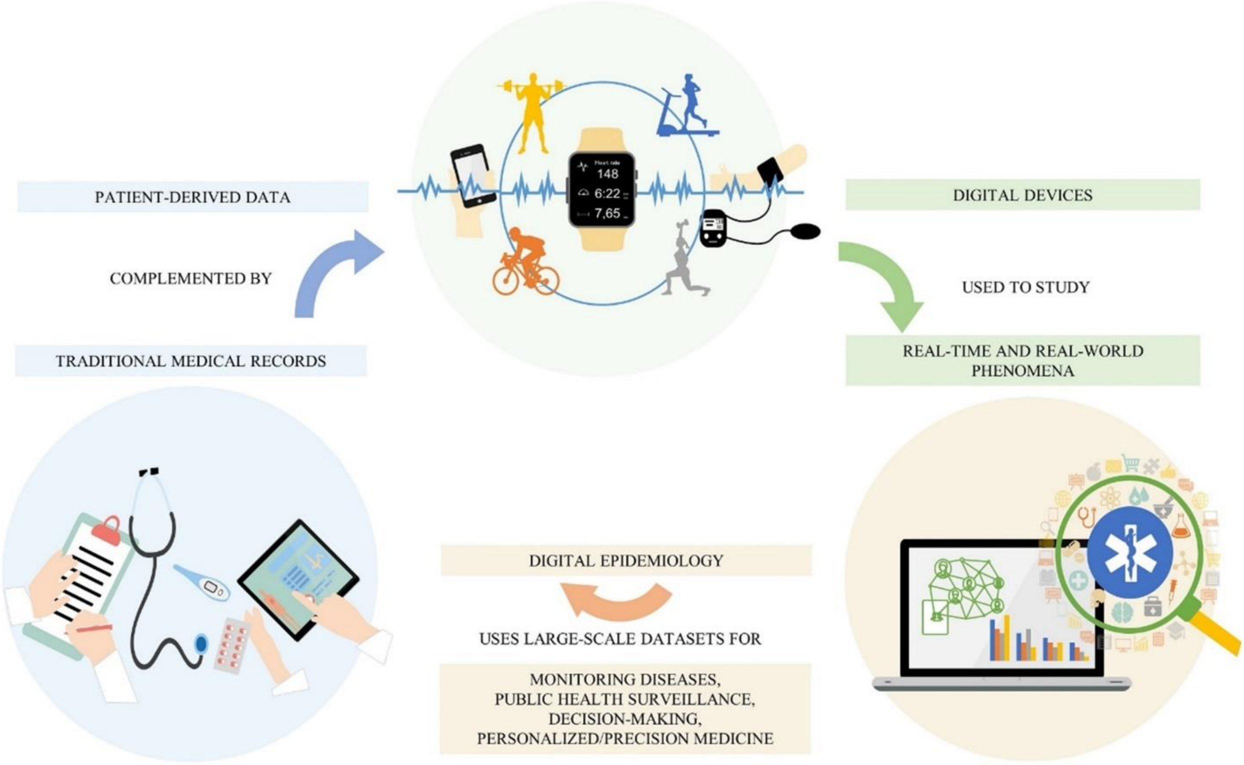

Figure 1: *Overview of the relationship between traditional medical records, digital devices and digital epidemiology, and its impact on health system and patient care.*

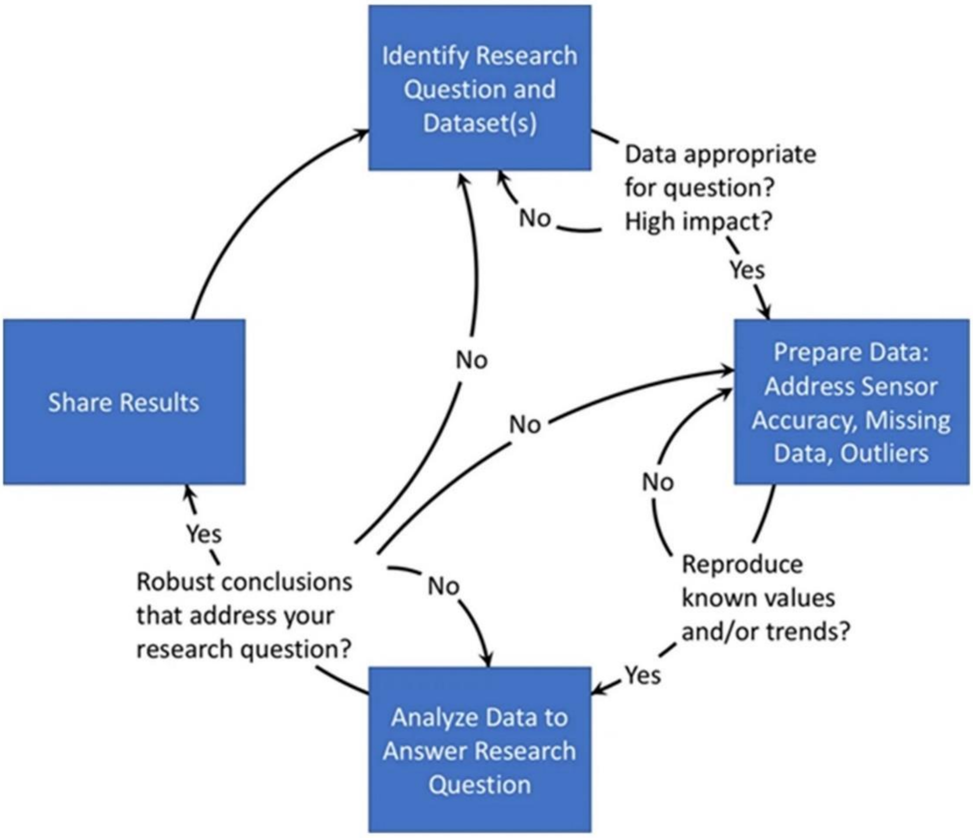

Figure 2: *Workflow for analyzing large-scale datasets from commercial devices to provide epidemiological insights.*

Advantages And Bias Of Metadata

As with any new type of information, patient-generated data and out-of-lab settings need further research to standardize the collection method. Large-scale studies, for example, have been conducted through the use of wearable devices by the mobile health company Azumio [529,530]. They realized a low-cost app, e.g., Argus, designed for every smartphone and suitable for studies involving a large cohort of subjects, especially when difficult to provide wearable sensors [531,532]. Mobile phone metadata have been already used effectively to monitor sleep [533], emotional states [534], transmission of diseases, such as malaria [535], and viruses [522], and to predict poverty and wealth in countries. The obvious advantage of this device is its widespread use, counting smartphone [536] owners in 69% of the population in developed countries and 46% in developing economies [530].

Although the ease with which these devices are commonly found in the population is an incentive to use them, their validity is not free from bias. Studies based on patient-derived digital data should describe the characteristics of the people examined to allow for good clustering of data and minimal variation between large samples. Selection bias can occur, as users may not represent a homogenous population, and information about gender, age, geographic location, socioeconomic status, race/ethnicity could lack; sensitivity or robustness testing is suggested [528]. Furthermore, wearable devices and smartphones need to be validated as digital tools, supporting the translation from the traditional tools used in common medical practice. A high rate of operator error and missing data should be considered as the patients themselves are responsible for the correct use of the devices. Long-term monitoring of patients is an attractive window of observation for physicians and researchers, even if these long times can lead patients to incorrect use of the device or withdrawal from the study. Positive feedback, self-management, and self-awareness can increase the program's adherence and reduce the withdrawal rate [537]. For example, PA monitor apps have a persuasive interface that reinforces and motivates attitudes to achieve or keep up with goals [538].

One drawback imposed by the use of digital devices is related to the mean age of the patients. Indeed, the elderly are discouraged from using applications and software; therefore, the subjects' age should also be considered, especially for OA disease which mostly involves the elders. However, this obstacle is most likely evident in the current historical period, when the older population struggles to adapt to the rapid technological advancements of modern electronics.

Data Privacy

Finally, specific guidelines for consent, data processing, and international security standards are fundamental to maintaining public trust, strengthening data privacy, and providing secure access to personal data [539]. On the contrary, the current trend of major internet services to strictly protect their data ownership may slow down the spread and growth of digital epidemiology, limiting the open access for researchers and public health organizations [520].

In the context of the COVID-19 outbreak, M.M. Mello and C.J. Wang [540] raised ethical issues linked to digital epidemiology, sustaining a powerful concept: "these new uses of people's data can involve both personal and social harms, but so does failing to harness the enormous power of data to arrest epidemics".

Guidelines To Monitor Physical Activity Through Wearables

Remote movement analysis can be as valuable as controversial, especially concerning patients who are not prone to technological advances. In the health promotion field, digital support can reach consumers in any way, via mobile phone or smartwatch. They represent a common, feasible, and low-cost tool for monitoring daily activities and PA for clinical and research purposes (Figure 3). In this review, we suggest the following guidelines when approaching the PA levels in OA analysis:

- Uploading data collected from smartwatches in real-time rather than during charging, preventing their loss.
- Preventing taking off the smartwatch or losing data through more extended battery life.

- Sending a maximum of 5 questions per day without a specific time frame, allowing the participants to answer at their convenience.
- Questions must be quick and easy to answer, taking up to 10 seconds.
- Patients can comment on their pain so that they can communicate their perceptions better.
- Analyzing different circumstances, e.g., sitting or standing, whereas these positions might cause severe pain.
- Introduce a simplified version of the WOMAC index to assess the OA physical functioning, administered through the smartwatch.

The following factors have to be considered to enhance the quality of physical activity:

- Increase motivation to perform PA by consulting personal achievements and progress.
- Strengthen adherence through the counseling of a personal trainer or physical therapist.
- Customize PA programs based on the subject's pain or difficulties.

Figure 3: *Recommended features to consider in the use of smartwatches for assessment of PA in OA patients.*

Perspective

Daily habits, like performing PA or sleeping, have a renowned effect on musculoskeletal, neurological, cardiovascular systems, and overall wellness. However, until the advent of modern technology, these behaviors were difficult to observe and quantify during their lifetime. Collecting the data from smartphones and wearables is a valuable method to study real-time and real-world habits, especially in subjects with diseases. This approach can stimulate significant changes towards a healthier lifestyle in people suffering from painful conditions such as OA to reduce pharmacological and surgical interventions and slow the progression of the disease; with personal, social, and economic gains. More specifically, the studies reported in here highlight the advantages in using digital devices in OA patients to encourage them to maintain and promote exercise. Finally, digital epidemiology has the conditions to be considered a preliminary tool for observing phenomena related to the health sphere, such as outbreaks of the disease, therapeutic effects of the medications, health surveillance, or how OA is perceived by the general public earlier than conventional health epidemiology. A fruitful collaboration between biomedical researchers and data scientists will be needed to exploit the exponential volume of information, directing commercial apps and devices towards improving health at the individual, group, and population levels.

Assessing Body Posture with Artificial Intelligence: Applicability and Reliability in Healthy Adult Population

Federico Roggio[1], Bruno Trovato[1], Martina Sortino[1], Marta Zanghì[1], Luca Petrigna[1], Alessandra Amato[1], Giuseppe Musumeci[1]

[1] Department of Biomedical and Biotechnological Sciences, Section of Anatomy, Histology and Movement Science, School of Medicine, University of Catania, Via S. Sofia n°97, 95123, Catania, Italy,

Preliminary results shared as oral presentation at the XIV Congress of the Italian Society of Exercise and Sport Science (SISMES)

Introduction

Many methods are available to evaluate posture, each with its own advantages and disadvantages [29]. For example, optoelectronic motion capture systems like Vicon or BTS are the gold standard for human movement analysis but are expensive and confined to laboratories [541]. Smartphone applications are portable and affordable, but their reliability can be limited [5].

Artificial intelligence (AI), specifically machine learning (ML) and deep learning, has revolutionized healthcare through advanced analytics. Traditional posture assessments often involve visual inspection, leading to subjectivity and inconsistencies among healthcare professionals like chiropractors and orthopedic surgeons [542]. An objective, AI-driven method holds the potential to overcome these limitations. Recognizing the importance of posture measurement in musculoskeletal health, there's a significant opportunity to apply AI techniques to enhance posture evaluation. Recently, accessible digital alternatives for human pose estimation have emerged. Libraries like MediaPipe [543], OpenPose [544] and MoveNet [545] offer skeletal-model algorithms ideal for research. Their strength lies in enabling quick posture or movement analyses via simple video or photo in any setting – a considerable advantage in clinical practice where timely, objective, and reproducible assessments are crucial [19]. MediaPipe, a sophisticated ML algorithm by Google, is designed for precise body pose tracking, capable of estimating 33 body landmarks [546]. As a robust framework, it excels in inferring data from video or photo inputs, making it perfect for rapid prototyping of perception pipelines in movement analysis.

Research strongly supports the validity of MediaPipe for the joint inference tracking technique. Recently, it has demonstrated that MediaPipe outperforms RGB-D cameras in joint angular estimation and exhibits close correlation with the gold-standard Qualisys motion capture system with a Pearson's correlation coefficients of 0.80 for lower limb and 0.91 for upper limb movements [547]. While additional research is needed to evaluate its practical applications and reliability across various settings, MediaPipe shows great promise, with proven validity in specific shoulder movement and gait analysis assessments [548].

Therefore, this scientific contribution aimed to shed light on the reliability and applicability of a ML approach for posture analysis, establishing standard data on the posture of healthy individuals.

Materials and Methods

We analyzed the posture of 100 males and 100 females, with an average age of 27.4 (SD ± 3.2) years. Participants were recruited from the Research Center on Motor Activities (CRAM) at the University of Catania, Italy. We collected a frontal and back photo with a camera placed on a tripod. A sample of 30 males and 40 females underwent the analysis twice to assess the reliability. We assessed the joint angles, as well as the horizontal and vertical angles using an algorithm capable of aligning the 3D position of the same landmarks in both the front and back photos. The study was approved by the Scientific Committee of the University of Catania's Research Center in Motor Activities (Protocol n.: CRAM-035-2023, 15 March 2023), and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from each participant.

For the pose estimation, MediaPipe analyzed the photos and extracted 33 anatomical landmarks. Based on their cartesian coordinates, we calculated various joint angles, distances between specific landmarks (like shoulder-elbow, hip-knee), and vertical and horizontal inclinations of vectors connecting those landmarks. On the coronal plane, we measured the shoulder, elbow extension, hip adduction, and knee varus/valgus angles. Similarly, on the sagittal plane, we calculated hip extension, knee extension, and ankle flexion angles, also measured as deviations from 180°. Lastly, using the lateral photo, we determined horizontal inclinations, namely the angle between a line connecting left and right landmarks with a horizontal line, and vertical inclinations, namely the angle between a line connecting two distinct landmarks with a vertical line.

Data Analysis

The data underwent three layers of analysis. We used R Project for Statistical Computing (Vienna, Austria) to assess the mean, standard deviation, and perform inference analyses. We used Python for building our algorithm model. Shapiro-Wilk test was used to verify the normality of the data, while Student's t-test and Mann–Whitney U test were used to identify any significant differences between men and women. Cohen's d was used to measure the effect size between the two groups. Then, we used the Intraclass Correlation Coefficient (ICC) to assess the reliability of this method when repeated with the same sample after a week.

Results

Our analysis revealed significant differences between sexes in several posture parameters. We calculated these parameters as the average 3D coordinates from the frontal and dorsal photos, Table 1. Specifically, we found differences in shoulder, elbow, and hip joint angles, with the most pronounced difference in hip angle (d = 1.67). However, knee angle did not exhibit a significant difference between sexes (d = 0.39). Additionally, we observed the greatest difference in vertical inclination for the neck (d = 0.66), but no significant difference for leg inclination (d = -0.09). All horizontal inclinations showed no significant sex-based differences, with low effect sizes. We used the ICC (3,k) to assess the consistency of posture measurements when repeated on the same participants after a week. The results demonstrated excellent reliability across all measurements, with ICC (3,k) values ranging from 0.67 to 0.95, Table 1.

Table 1. Results of the postural analysis with ML algorithms with gender differences

Postural parameters	Mean ± SD		Sig.	Effect size (d)	ICC
	Men	*Women*			
Body joints					
Shoulder angle (°)	16.12 ± 1.92	14.13 ± 1.53	< 0.001 ***	1.14	0.94
Elbow angle (°)	7.55 ± 3.56	4.43 ± 2.07	< 0.001 ***	1.07	0.93
Hip angle (°)	9.90 ± 2.22	6.71 ± 1.53	< 0.001 ***	1.67	0.95
Knee angle (°)	2.61 ± 1.02	2.24 ± 0.93	0.027 *	0.39	0.93
Horizontal inclinations					
Ears line (°)	2.04 ± 1.51	2.01 ± 1.15	0.550	0.02	0.79
Shoulders line (°)	1.18 ± 0.71	1.19 ± 0.89	0.740	-0.01	0.73
Elbows line (°)	1.17 ± 0.86	1.28 ± 0.93	0.530	-0.12	0.85
Wrists line (°)	1.33 ± 0.90	1.45 ± 0.91	0.408	-0.13	0.83
Hips line (°)	1.21 ± 0.77	1.52 ± 1.04	0.071 ·	-0.34	0.84
Knees line (°)	2.16 ± 1.30	2.11 ± 1.40	0.692	0.04	0.67
Ankles line (°)	1.93 ± 1.40	2.04 ± 1.34	0.581	-0.08	0.80
Vertical inclinations					
Neck inclination (°)	13.59 ± 3.19	15.36 ± 3.26	< 0.001 ***	-0.55	0.93
Trunk inclination (°)	2.28 ± 1.44	1.45 ± 1.05	< 0.001 ***	0.66	0.77
Body imbalance (°)	0.93 ± 0.43	1.25 ± 0.57	< 0.001 ***	-0.64	0.90
Leg inclination (°)	1.78 ± 0.58	1.83 ± 0.61	0.547	-0.09	0.80

Significance levels: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Cohen's d: > 0.50 = medium effect size, > 0.80 = large effect size. ICC= intraclass correlation coefficient (3,k)

Discussion

Posture assessment has broad applications in clinical and athletic settings, particularly for evaluating individuals with musculoskeletal and neurological disorders. This scientific contribution demonstrates the potential of a ML approach for posture analysis, providing standard data on healthy men and women. Additionally, we establish excellent test-retest reliability for this ML measurement technique.

Our results on sex-based differences in postural parameters were largely as expected. Significant differences were found in joint angles, but not in horizontal or vertical inclinations. This aligns with our assumption that healthy participants would not display significant postural asymmetries commonly seen in conditions like low back pain, stroke, cerebral palsy. The sex-based variations in body angles, most notably in the shoulder, elbow, and hip joints. Knee, neck, and trunk angles also showed statistical significance but with smaller effect sizes. Men exhibited larger shoulder and elbow angles, though the precise reason requires further investigation. Women showed greater neck inclination (medium effect size), possibly linked to factors like differences in neck isometric strength, neck girth, and head mass [549]. These findings offer valuable insights into understanding typical posture differences between sexes.

To evaluate the reliability of our measurement technique, we conducted a test-retest analysis on a group of participants, assessing the Intraclass Correlation Coefficient (ICC). Our findings revealed substantial to excellent reliability for both horizontal and vertical inclinations, with body joint measurements achieving excellent reliability. This corroborates with previous research that has investigated the reliability of similar methods. For instance, Ota et al. [550] evaluated the reliability of a motion capture system during bilateral squat exercises, reporting ICC values ranging from 0.92 to 0.96, indicating high reliability. Also Latreche et al. [551] assessed the reliability and accuracy of MediaPipe for specific rehabilitation exercises. They documented exceptionally high ICC scores for movements such as shoulder abduction, adduction, extension, and flexion, with values of 0.96, 0.99, 0.99, and 0.99, respectively. This evidence supports the robustness of our approach and highlights its potential application in clinical and rehabilitation settings.

We’ve introduced a novel, accessible method for postural analysis that focuses on identifying specific parameters reflecting distinct anatomical aspects and movement patterns. This approach has broad potential. The ease of use and absence of clothing removal make it ideal as a preventive screening tool. Beyond that, this method also shows promise within clinical settings. Unlike traditional postural analysis which often relies on subjective clinician observation, this approach could offer greater objectivity and accuracy. Identification of specific anatomical landmarks has value in diverse medical applications, from guiding proper exercise form to fall monitoring or supporting in-home rehabilitation. Similarly, the sports world could benefit from the method to analyze movement effectiveness and athlete performance.

This scientific contribution introduces a novel and accessible method for postural analysis with a focus on identifying specific parameters with the potential to reflect distinct anatomical variations and movement patterns. This approach shows promise across diverse contexts. Its ease of use and lack of clothing removal requirements make it potentially suitable for rapid preventive screenings. Additionally, the method holds considerable potential within clinical settings. By providing objective, quantifiable posture data, the method could improve upon subjective assessments used in traditional posture evaluations.

These preliminary results successfully demonstrate the feasibility of this innovative method and offers initial insights into postural variations. It represents the first step of a broader research activity, designed to explore the full potential of this approach. A primary goal is to expand upon the preliminary normative data established here by recruiting more diverse participant groups, representing various age categories and clinical populations. These expanded studies will help uncover how specific demographic variables and pathological conditions may influence posture. By refining the methods and correlating with relevant medical outcomes and movement performance metrics, we hope to generate evidence that ultimately establishes this technique as a robust tool for both preventative and diagnostic screenings.

Conclusion

This scientific contribution introduces a promising ML method for posture analysis, offering a convenient and objective alternative to traditional assessments. This initial exploration yielded insights into certain postural parameters that exhibit sex-related differences, alongside others that do not. The consistency of our findings over repeated measures was deemed to be excellent, underscoring the reliability of the approach in a preliminary context. Given the exploratory nature of this study, these findings should be viewed as preliminary. They lay the groundwork for future in-depth investigations that could expand on the identified trends, explore the implications of these postural characteristics further, and potentially apply these insights in clinical or athletic settings. The confirmation of our initial findings through larger, more diverse samples and additional studies would be an essential next step to solidify the foundation this research aims to build.

Chapter 4

Overview of the Ph.D. activities

4.1 Research areas of interest

During the Ph.D. course on Health Promotion and Cognitive Sciences, my research trajectory in the musculoskeletal field has been defined by a comprehensive and multidisciplinary approach, initially linked with the study of osteoarthritis, its relationship with physical activity, and the broader spectrum of musculoskeletal degeneration. This initial phase of my work involved an in-depth exploration of how lifestyle factors, especially physical activity, influence the onset and progression of osteoarthritis, shedding light on the intricate connections between daily activities, joint health, and overall musculoskeletal integrity. Building upon this foundation, my interest naturally evolved to encompass a wider range of non-invasive methodologies for movement and posture analysis. As my focus expanded to encompass MSDs more broadly, I began to question and investigate their prevalence, etiology, and impact on the quality of life. This exploration led me to delve into advanced methods for analyzing MSDs and analytical technologies that could offer deeper insights into these disorders.

The next phase of my research was characterized by the integration and application of various innovative methodologies. I extensively studied the potential of 3D markerless camera systems, which opened new possibilities in understanding human movement and biomechanics without the constraints of traditional marker-based motion capture. The use of infrared thermography became integral to my work, allowing for the non-invasive visualization of thermal patterns associated with inflammation and musculoskeletal anomalies. In tandem, I employed rasterstereography to gain precise three-dimensional insights into spinal alignment and postural deviations, crucial for diagnosing and monitoring spinal deformities and other postural-related disorders. Additionally, the exploration of mobile applications like PostureScreen and APECS marked a significant stride in making posture analysis more accessible and user-friendly. These tools not only facilitated widespread postural assessments but also empowered individuals to engage actively in managing their musculoskeletal health. The culmination of my research has been the incorporation of machine learning models such as MediaPipe. These AI-driven tools have been instrumental in elevating the accuracy and efficiency of analyzing complex movement patterns, offering substantial improvements in diagnosing, treating, and preventing musculoskeletal conditions.

My research areas, thus, encompassed a comprehensive approach, starting from the study of osteoarthritis and lifestyle factors to employing a suite of advanced technological methodologies. It reflects the commitment to understanding and addressing musculoskeletal health in its entirety, leveraging technology to uncover new insights and foster better health outcomes.

4.2 International Mobility

During my six-month period from January to June 2023 at the School of Sport, Exercise and Rehabilitation Sciences of the Birmingham University, I enhanced my knowledge in the field of muscle contraction and evaluation of the spine alterations. Under the esteemed guidance of Professor Deborah Falla, Director of the Centre of Precision Rehabilitation for Spinal Pain, my research experience was profoundly enriched and diversified. Initially, my engagement involved closely following and contributing to ongoing projects, notably the use of High-Density Electromyography. This period was instrumental in enhancing my understanding of muscle contraction changes during specific tasks, alongside hands-on experimentation with transcranial magnetic stimulation, vestibular stimulation, and isokinetic machines. Engaging with PhD colleagues from varied backgrounds such as engineering, physiotherapy, sports science, and psychology, I immersed myself in a multidisciplinary environment, which fostered a dynamic exchange of ideas and broadened my perspective, especially within the EMG field using tools like Matlab.

Transitioning from a phase of learning and observation, I collaborated with my supervisor to conceptualize and propose a project titled "A Digital Approach to Analyse the Execution of Functional Movements in People with and without Chronic Low Back Pain" to the scientific committee of Birmingham University. The project was grounded in the exploration of human motion estimation, positioned at the crossroads of traditional

3D methods and innovative markerless 3D techniques enhanced by machine learning (ML) applications. It aimed to validate and establish the reliability of ML algorithms, particularly MediaPipe by Google, in digitally analyzing human movement as compared to gold-standard 3D motion capture systems. Additionally, the project sought to utilize ML algorithms and infrared thermography to discern movement characteristics in individuals with and without chronic low back pain.

The project aimed to validate the reliability of specific ML algorithms, particularly MediaPipe, in digital human movement analysis compared to gold-standard 3D motion capture. Additionally, it sought to use these algorithms and IRT to differentiate movement characteristics and thermal patterns in individuals with and without chronic low back pain. The machine learning method provided detailed kinematic analyses of body landmarks to classify movement execution. In parallel, IRT captured thermal radiation patterns from the back before and after movements. These analyses distinguished between healthy individuals and those with chronic back pain, thereby demonstrating the potential alterations caused by the condition.

This endeavor necessitated a significant enhancement of my skills in Python and ML models, focusing predominantly on application of MediaPipe. Concurrently, I improved my proficiency with marker-based motion capture systems, particularly the BTS system comprising 8 optoelectronic cameras. The project encompassed a comprehensive analysis of both healthy and pathological participants undertaking a series of tasks including range of motion movements, walking, the functional reach test, the sit-to-stand test, and retrieving an object from the floor. This methodology integrated both the BTS system and standard cameras to provide a holistic view of movement analysis, blending traditional motion capture with innovative ML techniques.

4.3 Skills and tools

Throughout my three years of research, I have systematically developed a diverse set of skills and familiarized myself with a variety of tools critical to musculoskeletal research. In the first year, my focus was on building a strong foundation in statistics, coupled with learning coding for statistical analysis using R. This period also saw me acquiring practical knowledge in the use of 3D cameras and isoinertial systems. Simultaneously, I enhanced my proficiency in scientific English, improving my ability to articulate and disseminate research findings effectively. In the second year, my skill set expanded significantly with the introduction to infrared thermography, a technique I learned not only to use but also to analyze human thermograms. I delved into the application of rasterstereography and gained experience in using dynamometers, tools essential for accurate musculoskeletal assessment and analysis. The third year marked a significant transition towards advanced methodologies, where I immersed myself in the study of machine learning. This involved not only statistical applications but also exploring specific models for human pose estimation. Then, I improved my skills with inertial measurement units and how to use them for movement analyses. Furthermore, I developed proficiency in electromyography and the use of the high-density one, expanding my capabilities in muscle activity analysis and further enriching my research toolkit. This progressive skill development over the course of my PhD has prepared me with a comprehensive understanding of both the theoretical and practical aspects of musculoskeletal research, enabling me to utilize a multifaceted approach in my studies and contribute significantly to the field.

4.4 Titles of published papers as first or co-author

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4.5 Conferences attended

- 11th International Conference on Sport Sciences Research and Technology Support

  Roggio F, Di Grande S, Cavalieri S, Musumeci G. Digital Postural Analysis Using a Machine Learning Model: Applicability in Healthy Adults
- XIV Congresso Nazionale Società Italiana di Scienze Motorie e Sportive

  Roggio F, Trovato B, Sortino M, Zanghì M, Petrigna L, Amato A, Musumeci G. Assessing body posture with artificial intelligence: applicability and reliability in healthy adult population

  Trovato B, Roggio F, Sortino M, Zanghì M, Amato A, Petrigna L, Musumeci G. The effects of a static or dynamic stretching warm-up in preparing the knee for a change of direction exercise: a pre-post observational study

Sortino M, Roggio F, Trovato B,Petrigna L, Amato A, Zanghì M, Musumeci G. Infrared thermography analysis of the back during prolonged sitting. A proposal of active breaks

Zanghì M, Roggio F, Amato A,Petrigna L, Trovato B, Sortino M, Musumeci G. Innovative Exercise Approach for promoting sports inclusion in youth: expanding emotional and evolutionary intelligence through physical activity

Amato A, Petrigna L, Roggio F, Trovato B, Sortino M, Zanghì M, Musumeci G. Association between manual dexterity and postural sway orientation in a young population: a cross-sectional study

- XXIII Congresso Società Italiana di Analisi del Movimento in Clinica

  Roggio F, Musumeci G. Machine learning approach to detect the 3D human posture from a 2D image.

- 76° Congresso Nazionale Società Italiana Anatomia e Istologia

  Roggio F, Sortino M, Trovato B, Zanghì M, Amato A, Petrigna L, Di Rosa M, Musumeci G. Non-Invasive procedures for the Evaluation and Monitoring of Adolescent Idiopathic Scoliosis and Adapted Physical Activity Treatment.

  Lombardo C, Musumeci G, Roggio F, Loreto C. Ponticulus posticus and Malocclusion: a pilot morphological study in a Southern Italian pre-orthodontic cohort

- VII Safety Health Welfare in Agriculture & Agro-Food Systems Congress

  Rapisarda L, Matera A, Filetti V, Romano E, Scorciapino M, Musumeci G, Roggio F, Vitale E. Ergonomic evaluation in the use of manual agricultural tools: new analysis methodologies

- 28th Congress of the European College of Sport Science

  Roggio F, Petrigna L, Trovato B, Musumeci G. A combined infrared method with thermal imaging and rasterstereography to assess back changes in healthy individuals: a cross-sectional study

- XIII Congresso Nazionale Società Italiana Scienze Motorie e Sportive

  Roggio F, Petrigna L, Trovato B, Zanghì M, Sortino M, Musumeci G. Evaluation of the back of healthy individuals with thermography and rasterstereography

  Roggio F, Petrigna L, Trovato B, Zanghì M, Sortino M, Musumeci G. Evaluation of back muscles asymmetries in adolescent idiopathic scoliosis with infrared thermography

- 75° Congresso Nazionale Società Italiana Anatomia e Istologia

  Roggio F, Petrigna L, Trovato B, Zanghì M, Sortino M, Musumeci G. A non-invasive method for the evaluation of adolescent idiopathic scoliosis: morphological analysis of the spine with infrared thermography
- 74° Congresso Nazionale Società Italiana Anatomia e Istologia

  Roggio F., Trovato B., Lauretta G., Magrì B., Ravalli S., Musumeci G. Knee injury reduction through forefoot posture training in non-professional runners
- XII Congresso Nazionale Società Italiana Scienze Motorie e Sportive

  Roggio F., Ravalli S., Musumeci G. Postural changes through step frequency and metronome training to enhance knee peak force reduction in non-professional runners
- 93° Congresso Nazionale Società Italiana Biologia Sperimentale

  Roggio F, Musumeci G. Biomechanics changes in non-professional runners through step frequency and metronome training

4.6 Invited speaker communications

- 10th Etnean Occupational Medicine Workshop

  Presentation: Ergonomic and digital evaluation of work-related alterations
- Orthopedics and Rehabilitation Medicine "What scenarios are possible in a new system of alliances networking interventions for prevention, treatment and rehabilitation"

  Presentation: Thermography and rasterstereography as a combined infrared method to assess the posture of healthy individuals
- Sports, Law and New Technologies in Medicine

  Presentation: Non-invasive systems for digital assessment of human movement
- C.U.R.I.A.MO. WITH RESEARCH 2022

  Presentation: The counseling of adapted physical activity
- Friends of Morphology – Anatomy and Movement

  Presentation: Biomechanical alterations of the lower limb in non-professional runners

- Occupational trauma: a complex reality – Mediterranean Meeting

  Presentation: Posturometric and ergonomic assessment of work-related musculoskeletal alterations
- 75th CUS Catania – Sport, Disability and Inclusion – University of Catania

  Presentation: Digital systems for health promotion

4.7 Awards received

- Winner Start-Cup Sicily 2023

  Smart Knee project: a smart knee brace for the diagnosis of knee osteoarthritis
- Winner Start-Cup Catania 2023

  2nd Runner-up – Smart Knee project: a smart knee brace for the diagnosis of knee osteoarthritis
- Young Researcher in Motor and Sport Sciences Award – XIV National SISMeS Congress -Italian Society of Exercise and Sport Sciences

  1st Runner-up Oral Presentation: Assessing body posture with artificial intelligence: applicability and reliability in healthy adult population
- Best poster – XIII National SISMeS Congress – Italian Society of Exercise and Sport Sciences

  Presentation: Infrared Thermal Classification of the Spine of Sportive Individuals.
- Young Investigator Award – Best Videoposter 93rd National Congress of Experimental Biology

  Presentation: Biomechanics changes in non-professional runners through step frequency and metronome training

Chapter 5

5.1 Conclusions and future perspectives

This thesis has embarked on a comprehensive journey to explore and validate the efficacy of non-invasive methodologies in the screening, analysis, and management of MSDs, particularly focusing on adolescents and young adults. The underlying thread throughout this research has been the quest for innovative, accessible, and efficient diagnostic and treatment strategies that respond to the evolving landscape of MSDs in the modern world. A significant realization from this work is the crucial role of early detection and preventive strategies in combating the rising of MSDs, exacerbated by factors such as increasing sedentariness and lifestyle changes, especially evident during the COVID-19 pandemic. The exploration of technologies like infrared thermography, rasterstereography, and 3D markerless cameras, along with the use of mobile applications and advanced machine learning models like MediaPipe, has opened new perspectives in understanding and addressing the complexities of MSDs. These technologies have shown promise in offering more accurate, objective, and patient-friendly alternatives to traditional diagnostic methods. The integration of these innovative tools has not only enhanced my research for assessing and monitoring musculoskeletal health but also provided valuable insights into the development and progression of MSDs. By enabling early identification of potential musculoskeletal issues, these methods offer the potential to mitigate the long-term impacts of these disorders, particularly in vulnerable populations like AYAs. Furthermore, the application of these non-invasive techniques in real-world settings underscores their practicality and adaptability in diverse healthcare scenarios. The findings from this thesis emphasize the need for multi-dimensional and interdisciplinary strategies. It calls for continued innovation and research in developing and refining these methodologies, underscoring their potential to transform musculoskeletal healthcare and improve patient outcomes.

5.2 Future Perspectives

The future trajectory of my research in the musculoskeletal field points towards a multifaceted approach that integrates advanced technological methods with clinical practice. The promising results obtained from the application of 3D markerless cameras, infrared thermography, rasterstereography, mobile applications, and machine learning models pave the way for further innovation and refinement in diagnostic and therapeutic strategies. Future research will likely focus on enhancing the accuracy, efficiency, and user-friendliness of these technologies. The potential for developing more sophisticated machine learning algorithms and more intuitive mobile applications promises to make musculoskeletal health assessments more accessible and comprehensive. Additionally, the integration of these technologies into routine clinical assessments could revolutionize treatment approaches, enabling more personalized and preventive healthcare strategies.

An interdisciplinary approach involving biomechanics, data science, physiotherapy, and orthopedics is crucial for the continued advancement of musculoskeletal disorder analysis. Collaboration among these disciplines can lead to a more holistic understanding of musculoskeletal health and the development of innovative treatment methodologies. There is a need for large-scale and longitudinal studies to evaluate the long-term effectiveness and impact of these technologies in diverse populations. Such studies would provide valuable data for refining existing technologies and developing new ones, ensuring that they meet the varied needs of patients with different musculoskeletal conditions. Finally, the integration of these advanced diagnostic tools with digital health records and telemedicine platforms could facilitate better tracking of patient health outcomes and more coordinated care strategies, enhancing the overall quality of musculoskeletal healthcare.

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