UNIVERSITY OF BELGRADE

FACULTY OF SPORT AND PHYSICAL EDUCATION

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PACING STRATEGY IN HALF-MARATHON AND MARATHON BASED ON PERFORMANCE LEVEL, SEX AND AGE

Doctoral Dissertation

Belgrade, 2024

УНИВЕРЗИТЕТ У БЕОГРАДУ

ФАКУЛТЕТ СПОРТА И ФИЗИЧКОГ ВАСПИТАЊА

Љубица Д. Ристановић

СТРАТЕГИЈА ТЕМПА ТРЧАЊА ПОЛУМАРАТОНА И МАРАТОНА У ЗАВИСНОСТИ ОД ТАКМИЧАРСКЕ УСПЕШНОСТИ, ПОЛА И СТАРОСТИ

докторска дисертација

Београд, 2024.

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Expressions of Gratitude

At this pivotal moment of reaching the milestone of defending my doctoral dissertation, I reflect back on the beginning of my academic journey and realize that I never dreamed I would come this far. I would like to express my immense gratitude to everyone who has played a part in shaping my decisions and offered their unwavering support, regardless of whether or not they are mentioned below.

I express my deepest gratitude to my mother, who has been a constant source of support since the beginning of my academic career. She had already accomplished the greatest life task of any person on this planet – instilling values in her child. My brother and father have also stood firmly by my side, and I am grateful for their support and trust.

I extend immeasurable respect to my great teacher and mentor, Professor Stanimir Stojiljković. Recognizing my potential, he may have had the greatest influence on my decision to pursue the highest level of education and engage in work that gives me the feeling of fulfillment. Believing in me, he fought alongside me until we accomplished all of the academic goals that we set together.

I owe gratitude to another mentor of mine, Assistant Professor Ivan Ćuk, for the idea for the doctoral dissertation and his help on the path to reaching the point of its defense.

A big thank you to all my friends who have been with me every day, offering their advice and selfless support in all aspects of life.

I would like to express my heartfelt gratitude to my fellow runners for being a constant source of inspiration from start to finish of each of my academic paper endeavors.

I would also like to thank the coaches at the Mladenovac karate club, who taught me discipline, perseverance, and respect for others since my school days. I am also grateful to my physical education teachers at schools I attended, who have been a shining example of the beauty of our profession.

Lastly, I am infinitely grateful to my life companion, my spouse Boris, who has shown trust in me and given me the privilege to allowed us to grow as parents together, earning a special place among the most important people in my life.

Изјаве захвалности

Освртањем на почетак свог академског путовања, схватам да нисам ни сањала да ћу стићи до одбране докторске дисертације. Изразила бих велику захвалност свима који су на било који начин допринели мојим одлукама и били уз мене, без обзира на то што нису појединачно поменути.

Изражавам највећу благодарност својој мами која је од почетка тоје *академске каријере имала само улогу подршке, јер је до тада завршила највећи животни посао сваког човека на овој планети – усађивање вредности код свог детета. Уз мене су чврсто стајали и брат и тата, којима сам захвална на подршци и поверењу.*

Неизмерно поштовање исказујем свом великом учитељу и ментору, професору Станимиру Стојиљковић. Препознавши у мени квалитет, можда је имао највећи утицај да се одлучим за корак ка највишем степену образовања и радим посао који ме чини задовољном. Верујући, борио се са мном до остварења свих мојих академских циљева, које смо претходно заједно поставили.

Захвалност дугујем и свом другом ментору, доценту Ивану Ћук, за идеју докторске дисертације и помоћ да дођем до овог дана.

Велико хвала мојим пријатељицама, које су уз мене свакодневно делећи несебичне савете и подршку у свим аспектима живота.

Мојим тркачима желим да изразити дубоку захвалност за то што су ми били извор инспирације за све академске радове које сам успешно завршила.

Захвалила бих се и тренерима карате клуба „Младеновац“ који су ме од школских дана, учили дисциплини, упорности и поштовању других особа. Такође, својим професорима физичког васпитања у школи, који су ми примером указали на лепоту наше струке.

На крају, бескрајно сам захвална свом животном сапутнику, супругу Борису, који ми је подарио поверење и привилегију да се заједно остваримо као родитељи и заузео посебно место на трону најважнијих особа у мом животу.

Pacing strategy in half-marathon and marathon based on performance level, sex and age

Abstract

Pacing strategy (PS) is a key factor in long-distance running which influences performance by managing the intensity of effort throughout the race. The aim of this research was to analyze and compare PSs among half-marathon and marathon runners based on performance level, sex and age. The sample included 233,083 runners who finished the Vienna Half-Marathon (N=150,232) and Marathon (N=82,815) races from 2006 to 2023. The analysis utilized official data from the organizer's website.

PS was analyzed using five segments for both races. For the half-marathon, the course was divided into four 5 km and one 1.0975 km segments, whereas each marathon segment was twice as long. Percentage values of average change of speed for each segment ($CS_{1–5}$) were calculated relative to the overall race speed. The absolute change of speed for the entire race (ACS) was the average of the five CS values. The performance groups were defined as quartiles based on race placement.

A positive PS with an end spurt (ES) and varying segments was observed in almost all runner subgroups, regardless of the race type, performance group, sex, and age. Faster runners exhibited a more consistent PS compared to slower runners. Slower runners had a higher ES compared to faster ones. Significant difference in ACS between races within each performance group was observed.

Male runners had lower ACS than female runners in the half-marathon, while the opposite trend was observed in the marathon. The differences between sexes were more pronounced in the marathon compared to the half-marathon. Female runners showed a higher ES than male runners.

In the half-marathon, male runners aged 40–59 and female runners aged 40–49 exhibited a more evenly distributed PS compared to younger and older runners. In the marathon, runners aged 30–49 showed a more consistent PS regardless of sex. Among male runners, each age group displayed a more even PS in the half-marathon compared to the marathon, while no significant difference was found among female runners. In the half-marathon, the youngest runners, regardless of sex, exhibited the fastest ES. In the marathon, the fastest ES was displayed by the youngest male runners and by both the oldest and youngest female runners.

Key words: long-distance running, long-distance races, pacing, running speed, speed variability, age group.

Scientific field: Physical Education and Sport

Scientific subfield: Physical Education, Sport and Recreation Sciences

UDK: 796.422.16.05(043.3)

Стратегија темпа трчања полумаратона и маратона у зависности од такмичарске успешности, пола и старости

Сажетак

Стратегија темпа (СТ) је кључни фактор који утиче на такмичарску успешност (ТУ) у трчању на дуге дистанце, управљајући интензитетом напора током трке. Циљ овог истраживања је био да анализира и упореди СТ код тркача на полумаратону и маратону, у зависности од нивоа ТУ, пола и старости. Узорак испитаника је чинило 233.083 тркача који су завршили трке у полумаратону (N=150.232) и маратону (N=82.815) у Бечу, од 2006. до 2023. године. За анализу су коришћени званични подаци са интернет странице организатора.

СТ је анализирана кроз 5 сегмената обе трке. У полумаратону, стаза је подељена на четири сегмента од 5 км и један од 1.0975 км, док је сваки сегмент у маратону двоструко дужи. Проценат просечне промене брзине сваког сегмента ($ППБС_{1–5}$) израчунат је у односу на укупну брзину трке. Апсолутна промена брзине целе трке (АПБ) је израчуната као просечна вредност пет ППБС вредности. Групе према ТУ су креиране као квартили на основу пласмана на трци.

Позитивна СТ са крајњим убрзањем (КУ) и различитим сегментима примећена је у готово свим подгрупама тркача, без обзира на врсту трке, ТУ, пол и старост. Бржи тркачи су показали равномернију СТ у поређењу са споријим тркачима. Спорији тркачи су имали израженије КУ у поређењу с бржим тркачима. Примећена је значајна разлика у АПБ између трка унутар сваке групе ТУ.

Мушкарци су имали нижи АПБ од жена у полумаратону, док је супротан тренд примећен у маратону. Разлике између полова су биле израженије у маратону у поређењу са полумаратоном. Жене су имале веће КУ у односу на мушкарце.

Мушкарци старости од 40 до 59 година и жене старости од 40 до 49 година су имали равномернију СТ у поређењу с млађим и старијим тркачима у полумаратону. У маратону су тркачи старости од 30 до 49 година имали равномернију СТ без обзира на пол. Код мушкараца је равномернији темпо примећен унутар сваке старосне категорије у полумаратону у поређењу са маратоном, док код жена није било значајне разлике. Најмлађи тркачи су имали најизраженије КУ код оба пола у полумаратону. У маратону, најмлађи мушкарци су имали најизраженије КУ, док су и најстарије и најмлађе жене имале најизраженије КУ.

Кључне речи: трчање на дуге дистанце, трке на дуге дистанце, темпо, брзина трчања, промена брзине, старосна категорија.

Научна област: Физичко васпитање и спорт

Ужа научна област: Науке физичког васпитања, спорта и рекреације

УДК: 796.422.16.05(043.3)

Abbreviations:

ACS – Absolute Change of Speed throughout the entire race

ANOVA – Analysis of Variance

ATP – Adenosine Triphosphate

CS – Change of Speed

$CS_{1–5}$ – Change of Speed for each of the five segments

CV – Coefficient of Variation

DS – Descriptive Statistics

ES – End Spurt

HIIT – High-Intensity Interval Training

HL – High-Level performance group

ibid. – In the same place (this abbreviation was used when a previous reference is repeated)

LL – Low-Level performance group

Max – Maximal value

Mean – Mean value

MHL – Moderate to High-Level performance group

Min – Minimal value

MLL – Moderate to Low-Level performance group

MLSS – Maximal Lactate Steady State

N – Number of participants

$ŋ^2$ – Eta-squared

OBLA – Onset of Blood Lactate Accumulation

PS – Pacing Strategy

RCP – Respiratory Compensation Point

RPE – Rating of Perceived Exertion

SD – Standard Deviation

VO_2 – Volume of Oxygen Consumption

VO_2max – Maximum Oxygen Consumption

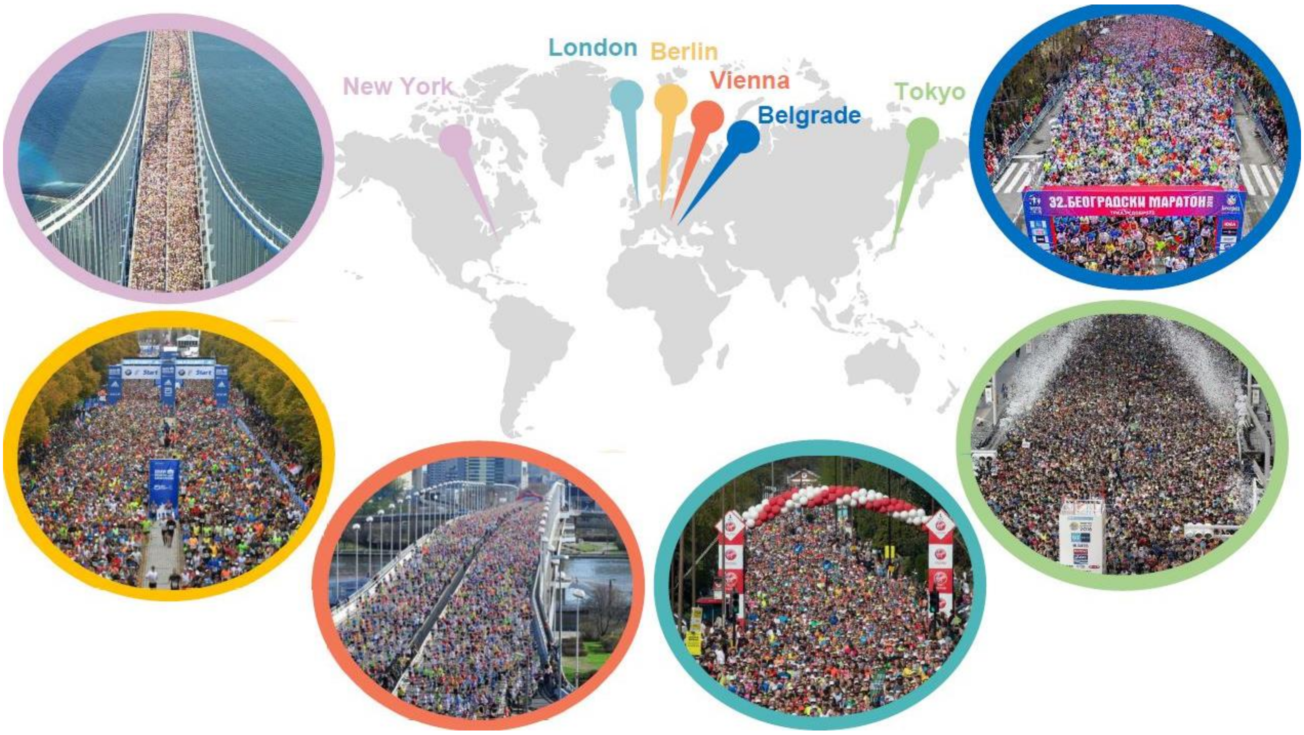
W’ – Work Capacity above Critical Power

Λ – Lambda

Content

1. INTRODUCTION

Long-distance running, recognized as a rigorous endurance activity, has become increasingly popular worldwide (Picture 1) over the past 50 years (Knechtle et al., 2018; Vitti et al., 2020). As the number of participants in long-distance races, both domestically and internationally, continues to grow, the overall performance results have been declining year after year, coinciding with an increase in the number of older age group runners (Knechtle et al., 2018; Stojiljković et al., 2019, 2022; Vitti et al., 2020). However, when considering only the top 10 finishers, the results have been improving (Knechtle et al., 2018). The average marathon time from 1997 to 2017 was recorded as 02:12:23 (h:min:s), showcasing a notable improvement compared to the period from 1897 to 1917, during which the average time stood at 02:48:09 (ibid.). At the Belgrade Marathon, from 2007 to 2019, the majority of participants completed the race with times between 4:00 and 4:30 h:min (Stojiljković et al., 2022). These data highlight the growing presence of recreational runners who are actively involved in training processes and the advancements in training technologies benefiting elite runners (Bermon et al., 2021; Ruiz-Alias et al., 2023).



Picture 1. The Massiveness of Participants in Long-Distance Races Worldwide in 2019 (The image was created by the author of this thesis, sourcing available pictures from the internet and integrating them into a composition using a PowerPoint template).

1.1.Long-Distance Running

Athletics, as a sports discipline, encompasses a comprehensive range of 49 events, which include throws, jumps, various running events, race walking, and combined events (World Athletics Series Regulations, 2023). Running falls under the category of athletics encompassing short, middle, and long distances. Long-distance running includes events such as the 3,000 m steeplechase, 5,000 m, and 10,000 m on the track. Moreover, it comprises races conducted on city streets and/or mountains, such as the 5 km, 10 km, 21.0975 km (half-marathon), 42.195 km (marathon), and distances exceeding 42.195 km (ultramarathon) (Ćuk & Rakić, 2019; World Athletics, 2024), often characterized by diverse terrains. The marathon is the only running event organized outside the track and is featured in the World Athletics Championships and the Olympic Games. It was introduced as a new discipline in the inaugural modern Olympic Games held in Athens in 1896 (Stefanović et al., 2008; World Athletics, 2022b). While the half-marathon is not included in the World Athletics Championships or the Olympic Games, it is part of the World Athletics Half Marathon Championships, which take place every two years since 1992 (World Athletics, 2022a).

In recent decades, there has been a significant increase in the number of running events worldwide, accompanied by a rise in the number of participants across all running disciplines outside the athletics track (Picture 1). The world records for the 5 km race stand at 12:49 min:s for men, 14:29 min:s for women (women-only participants), and 14:19 min:s for women (combined women and men participants) (World Athletics, 2024). The slowest of recreational runners typically take over 1 hour to complete (*Credit Union Cherry Blossom*, 2023). For the 10 km race, the current world records are 26:24 min:s for men, 30:01 min:s for women (women-only participants), and 29:14 min:s for women (combined women and men participants) (World Athletics, 2024), while the slowest recreational runners finish in over 1:15 h:min (Cuk et al., 2019; *Vienna City Marathon*, 2023). The current world record for the men's half-marathon is 57:31 min:s. For women, it is 1:05:16 h:min:s (women-only participants), and 1:02:52 h:min:s (combined women and men participants) (World Athletics, 2024), while recreational runners generally have a time limit of 3 hours to complete the race. The current world record in the marathon is 2:00:35 h:min:s for men, 2:17:01 h:min:s for women (women-only participants), and 2:14:04 h:min:s for women (combined women and men participants, allowing women to run alongside or behind men, reducing wind resistance and enabling better performance) (World Athletics, 2024). The slowest among recreational runners finish the race in just over 6 hours (*Belgrade Marathon*, 2023; *Vienna City Marathon*, 2023). Based on these race results from around the world, it is evident that recreational runners take several times longer to complete races compared to elite athletes. We can conclude from this observation, that running the same distance does not entail the same level of exertion for athletes and recreational runners (Monte et al., 2020; Seene et al., 2005). Given that recreational runners comprise the majority of participants in mass long-distance running events worldwide, it is important to recognize and highlight the contributions of long-distance running to overall health and quality of life.

1.1.1. The Health Aspects of Long-Distance Running

Long-distance running, as a form of endurance training, has been associated with numerous positive physiological effects (Davies, 2018; Papić et al., 2019), and overall health improvements, regardless of the distance (Wirnitzer et al., 2022). Some of the positive effects of long-distance running include increased maximum oxygen consumption (VO_2max), enhanced respiratory capacity, improved running economy, reduced blood lactate concentration at submaximal intensity, increased density of mitochondria and capillaries, improved enzymatic activity, and reduced body fat (Swank & Sharp, 2016). The increase in VO_2max is attributed to factors such as increased stroke volume of the heart, elevated blood volume, increased capillary density, and increased mitochondrial density in trained muscles (Costill et al., 1976). The growing number of participants in these disciplines could potentially lead to significant health improvements and increased life expectancy, reducing the risk of cardiovascular and malignant diseases by up to 30% (Pedisic et al., 2020). However, there is also a significant risk of health issues associated with long-distance running (Hollander et al., 2018). Excessive doses of running training do not necessarily have a favorable association with mortality (Pedisic et al., 2020) and health (Toresdahl et al., 2021, 2023). Excessive training can lead to a decrease in a person's work capacity due to the dominance of catabolic processes, causing an imbalance between catabolic and anabolic processes in the body (Seene et al., 2005). Therefore, long-term health issues resulting from ultra-endurance running may include potential maladaptation in various organ systems, such as the renal, cardiovascular, immunological, gastrointestinal, respiratory, musculoskeletal, neurological, and integumentary systems (Scheer et al., 2022). The risk of developing diseases due to high absolute training loads is higher in recreational and lower-ranked athletes (Shephard & Shek, 2015) compared to elite athletes (Malm, 2006).

In addition to metabolic imbalances, excessive training load and/or load progression can increase the risk of running-related injuries (Damsted et al., 2018). The prevalence of these injuries ranges from 36% to 63.5% (Gomes Neto et al., 2023) and is more common in less experienced runners (Damsted et al., 2019; Papić et al., 2021) and slower runners (Damsted et al., 2019). Therefore, it is important to maintain the upward trend of mass participation in long-distance running events while ensuring proper guidance and dosage of the training process.

The increase in the number of runners participating in these races can be attributed to various factors, including the desire to compete with oneself and others, as well as the aspiration to lead a high-quality lifestyle for longer (Hongwei & Resza, 2021; Juhas & Repić-Ćujić, 2016). It can be assumed that races serve as significant motivation for runners to continue their running journey and strive for better results. Therefore, it is important to examine the factors that influence running performance.

1.1.2. Factors that Influence Performance in Long-Distance Running

1.1.2.1. External Factors

Several crucial external factors significantly influence performance in long-distance running. These factors encompass the profile and quality of the track (surface type, number of curves, length, and gradient of uphill and downhill sections), environmental conditions (altitude, temperature, relative humidity, and wind speed) (El Helou et al., 2012; Ely et al., 2008; Knechtle, McGrath, et al., 2021; Leslie et al., 2023; Mantzios et al., 2022; Vihma, 2010; Weiss et al., 2022), nutrition and hydration before/during the race (Burke et al., 2019), warm-up (Alves et al., 2023), pacing strategy, drafting, footwear (Barnes & Kilding, 2019; Hoogkamer et al., 2019) and clothing (Hoogkamer et al., 2017; Joyner et al., 2011). Regarding environmental conditions, it is noteworthy that thermoregulatory strain is lower on days with high temperature, low humidity, and low wind speed (Knechtle, McGrath, et al., 2021). Specifically, even a mere 1 °C an increase in the heat index (which combines temperature and humidity) can slow down elite marathon runners by approximately 0.35 minutes (Leslie et al., 2023).

1.1.2.2. Internal Factors

In addition to external factors, every runner is influenced by internal factors that encompass the coordinated interplay of muscular, cardiovascular, and neurological elements. These factors work in harmony to effectively convert energy from aerobic and anaerobic adenosine triphosphate (*ATP*) into speed and power (Joyner & Coyle, 2008).

It is well known which physiological factors significantly impact the performance of elite long-distance runners: VO_2max (Billat et al., 2001); the fraction of VO_2max that can be sustained throughout a race (*Fractional VO_2max Utilization*) (di Prampero et al., 1986), closely associated with the lactate threshold or critical running speed (Tanaka & Matsuura, 1984) and oxygen uptake at submaximal running intensities (i.e., running economy in ml of O_2/kg/km) (Conley & Krahenbuhl, 1980; Jones, 2006; Joyner, 1991; Joyner et al., 2011). The lactate threshold, or maximal lactate steady state (*MLSS*), represents the highest exercise intensity at which there is still a balance between lactate production and elimination (Heck et al., 1985; Tegtbur et al., 1993). VO_2max represents the maximum volume of oxygen that an individual can uptake and utilize per minute to produce energy for muscular work (Stojiljković et al., 2012). The critical speed represents the intensity threshold beyond which VO_2max cannot be achieved. However, when running at speeds higher than the critical speed and with sufficient duration, VO_2max can be attained (Hill & Ferguson, 1999).

During physical exercise that activates large muscle groups, such as running, the transportation of oxygen through circulation is the main (75%) limiting factor for VO_2max. However, in exercises involving small muscle groups, this role is reduced to 50% (di Prampero, 2003). The range of VO_2max values varies depending on the individual's level of physical activity. Sedentary individuals typically have VO_2max values of ~ 20 ml/kg/min (Chidnok et al., 2020), whereas highly trained cross-country skiers have recorded the highest values (Sandbakk & Holmberg, 2014). Male athletes in this category typically exhibit values of 80–90 ml/kg/min, while female athletes show values of 70–80 ml/kg/min (ibid.). In elite male long-distance runners, VO_2max values generally fall between 70 and 85 ml/kg/min (Pollock, 1977). Female runners, on the other hand, tend to have values approximately 10% lower due to factors such as lower hemoglobin concentration and higher levels of body fat (Durstine et al., 1987; Pate et al., 1987). In addition to VO_2max, male athletes also have higher values for the speed at which they begin to accumulate lactate (*Onset of Blood Lactate Accumulation – OBLA*) and the lactate threshold compared to female athletes. However, female athletes achieve the speed at OBLA and lactate threshold at a higher percentage of their VO_2max (91.1±3.1% and 86.4±3.3%) (Maldonado-Martin et al., 2004). Regarding performance in different age groups, female runners achieve their best marathon performance in the 30–34 years age category, while male runners achieve it approximately 5 years older, in the 35–39 years age category (Nikolaidis, Rosemann, & Knechtle, 2018). There are also assumptions that the decline in these physiological functions caused by aging does not differ between male and female individuals (Lepers & Cattagni, 2012), as evidenced by the comparable performance dynamics of runners aged 20 to 60 years in long-distance races (De Leeuw et al., 2018). Elite long-distance runners are capable of sustaining running speeds that require 85–90% of VO_2max for over an hour (Joyner, 1991; Joyner & Coyle, 2008). Understanding the aforementioned factors, and also the oxygen cost of running at a specific running speed (*running economy* – VO_2/velocity), allows for a reliable estimation of marathon pace (ibid.). In other words, running economy can influence the pacing strategy for long-distance running (Damasceno et al., 2011; Lima-Silva et al., 2010). A more economical runner can maintain a faster pace before experiencing lactate accumulation (Fay et al., 1989). With similar values of VO_2max, lactate threshold and running economy, i.e., the running speed at which VO_2max is reached, will likely be decisive for performance (Conley & Krahenbuhl, 1980; Joyner, 1991; Larsen, 2003; Lucia et al., 2006; Morgan et al., 1989; Santos-Concejero et al., 2015). In a study by Santos-Concejero et al. (2015), elite long-distance runners from Europe exhibited significantly higher VO_2max values compared to elite Eritrean runners (77.2 ml/kg/min and 73.5 ml/kg/min, respectively), while the Eritrean runners demonstrated superior running economy (191.4 ml/kg/min and 205.9 ml/kg/min). However, the Eritreans achieved significantly better results in the 10 km race compared to the Europeans (27.7 min and 28.5 min, respectively), and running economy was significantly correlated with performance. Some authors estimate that the conditions for achieving a sub-two-hour marathon would require a runner to weigh 59 kg and maintain a VO_2 of approximately 4.0 l/min or 67 ml/kg/min (Jones et al., 2021).

During prolonged submaximal activities, the ability of an athlete to minimize energy expenditure becomes a crucial factor for performance and a valid indicator of efficiency (Conley & Krahenbuhl, 1980; Lacour et al., 1990; Morgan et al., 1991). Energy expenditure (oxygen uptake) during movement can be defined as the amount of energy expended per unit distance (ml O_2/kg/km or J/kg/km) (Ferretti, 2015). Estimating energy expenditure is a valuable approach for examining the influence of individual efficiency on performance across various forms of locomotion (Brisswalter et al., 1998; Hausswirth et al., 1997). To ensure the accuracy of these estimations, it is important to apply this principle under stable metabolic conditions (50–80% VO_2max) where VO_2max is representative of energy expenditure per unit of time (Hausswirth & Lehénaff, 2001). The validity of these estimations is particularly relevant for submaximal intensities, which are commonly encountered in half-marathons and marathons.

1.1.2.2.1. Energetics of Long-Distance Running

Since aerobic physical work relies on the oxidation of substrate “fuels” in working muscles, through well-defined chemical reactions, the rate at which these muscles take up oxygen from the bloodstream reflects their rate of fuel consumption and, consequently, their maximum power output (Rapoport, 2010). Endurance performance in running is influenced by several physiological factors, with aerobic capacity (VO_2max) and the energy cost of running being the primary ones mentioned. However, there are additional factors that appear to limit performance at the highest levels achieved by elite marathon runners, such as heart morphology and lactate kinetics during exercise (in male individuals), adiposity, and iron levels in the blood (in female individuals) (Legaz Arrese et al., 2006).

The key metabolic substrates for activating muscle contractions during long-distance running are carbohydrates (derived from liver, muscle glycogen, and plasma glucose) and fats (including intramuscular triglycerides and free fatty acids in plasma released from adipose tissue) (Rapoport, 2010). In marathon running, the contribution of anaerobic metabolism is relatively small, but it becomes more significant in races lasting 13–30 min (5 and 10 km races), accounting for approximately 10–20% of total ATP turnover (Joyner & Coyle, 2008). In endurance sports, even athletes with the lowest, extremely low percentage of non-essential fats (≈ 2%) have enough stored metabolic potential energy to complete more than four marathons if working muscles could derive energy exclusively from fats (Rapoport, 2010). In contrast, the stores of physiological carbohydrates are very limited (Rodriguez et al., 2009). Previous research suggests that carbohydrate intake and energy expenditure (kJ/kg/d) before and during a marathon race are positively associated with runners’ performance (Jeukendrup, 2004; Mahon et al., 2014; Rapoport, 2010). Consuming sports drinks containing carbohydrates and electrolytes before, during, and after such activities helps maintain blood glucose levels, supplies muscles with energy, and reduces the risk of dehydration and hyponatremia (Rodriguez et al., 2009). Low energy intake can lead to adverse effects such as loss of muscle mass, disruption of the menstrual cycle, loss or lack of increased bone density, increased risk of fatigue, injury, and illness, and prolonged recovery process (ibid.). Some authors indicate that there is no significant difference in supplementation intake patterns among runners participating in different long-distance disciplines (Wirnitzer et al., 2021).

The proportion of energy derived from carbohydrates and/or fats during running depends on the intensity of running (Figure 1), as well as the size of glycogen reserves. At higher intensities, a larger proportion of energy comes from carbohydrates, while fats become a more significant energy source as glycogen stores are depleted (Romijn et al., 1993). However, the proportion of energy obtained from a specific source (macronutrients – carbohydrates, fats, and proteins) also depends on the predominant type of muscle fibers in an individual’s working (leg) muscles (Schröder et al., 2008). In elite long-distance type I runners, with 60–70% fast glycolytic and oxidative fibers, the daily energy expenditure is approximately 3750 kcal (ibid.). In type II runners, who have an equal distribution of slow and fast fibers, the energy expenditure is around 3463 kcal (ibid.). Lastly, type III runners, with 60–70% slow fibers, have a daily energy expenditure of approximately 3079 kcal (ibid.). In their study, daily carbohydrate expenditure averages around 10 g/kg for type I runners, around 8.0 g/kg for type II runners, and 4.7 g/kg for type III runners (ibid.). However, for runners of all muscle fiber types in leg muscles, the daily carbohydrate expenditure was approximately the same (around 10 g/kg) due to the intensity levels at or above VO_2max (ibid.).

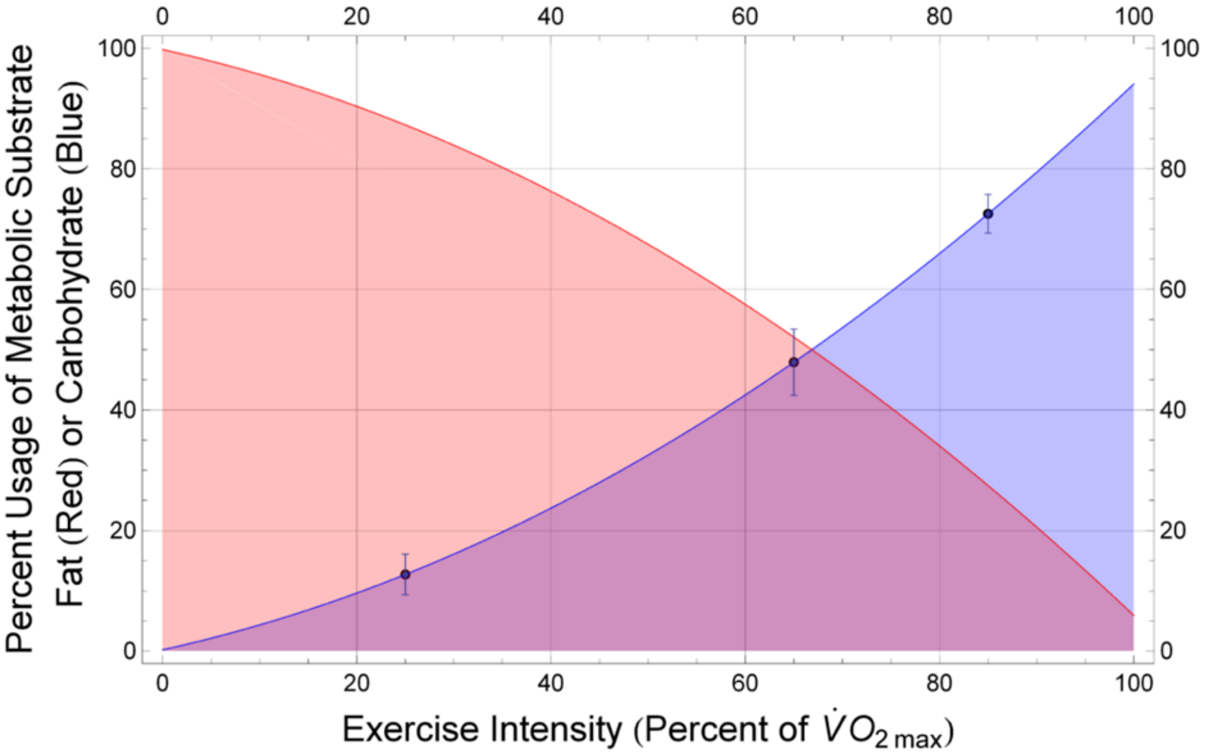


Figure 1. Relative utilization of fats (red color – free fatty acids/muscle triglycerides) and carbohydrates (blue color – plasma glucose/muscle glycogen) as metabolic fuels depending on exercise intensity – %VO_2max (data points correspond to the study by Romijn et al. (1993), and the figure was sourced from the study by Rapoport (2010, pp. 4)).

In the literature, intensity is divided into different zones based on physiological mechanisms of energy production and certain parameters such as lactate or ventilatory threshold and VO_2max. The number of intensity zones can vary but typically ranges from three to seven (Friel, 2016; Seiler & Kjerland, 2006; Seiler & Tønnessen, 2009). The characteristics of the five intensity zones are shown in Table 1.

Table 1. *Characteristics of five intensity zones created by the Norwegian Olympic Federation (adapted from Seiler, 2010)*

Intensity zone	**VO_2 (%max)**	**Heart rate (%max)**	**Lactate (mmol·L^{-1})**	**Typical accumulated duration within the zone**
1	50–65	60–72	0.8–1.5	1–6 h
2	66–80	72–82	1.5–2.5	1–3 h
3	81–87	82–87	2.5–4	50–90 min
4	88–93	88–92	4.0–6.0	30–60 min
5	94–100	93–100	6.0–10.0	15–30 min

Based on the results of highly trained long-distance runners and considering the information in Table 1, we can say that a 5 km race typically takes place in Zone 5, a 10 km race falls between Zone 4 and 5, a half-marathon is in Zones 3 and 4, while a marathon is run in Zones 2 and 3. Correspondingly, a 5 km race occurs near VO_2max, a 10 km race at around 90–100% VO_2max, a half marathon at approximately 78–88% VO_2max, and a significant portion of the marathon is run at an intensity of about 75–85% VO_2max (Bassett & Howley, 2000; Billat et al., 1994; Joyner & Coyle, 2008). For less trained runners, such as recreational runners, the percentage of VO_2max at which they can maintain their pace during a race is lower, so they typically run at a slightly lower relative intensity compared to highly trained runners (Bassett & Howley, 2000). For recreational runners, marathon races occur at a lower intensity (Zones 1 and 2), while half-marathons are run at a moderate intensity (Zones 2 and 3). During low and moderate-intensity activities, the primary source of energy is fats (Bytomski, 2018). However, in the case of highly trained athletes, the intensity in running these distances is very close to the lactate threshold, beyond which the body cannot extract energy from fats quickly enough, making it crucial to have sufficient carbohydrate reserves (Noakes et al., 2014). Moreover, the total carbohydrate reserves from muscle glycogen, liver glycogen, and plasma glucose are not sufficient for running longer than approximately two hours (Impey et al., 2020; Joyner & Coyle, 2008; Rapoport, 2010). While glycogen from the liver can be available to metabolically active cells (including working myocytes) throughout the body through glycogenolysis and the release of glucose into the bloodstream, glycogen in myocytes can only be used by the cell in which it is synthesized and stored (Rapoport, 2010). The reason for this difference is that myocytes, unlike hepatocytes, lack the enzyme glucose-6-phosphatase, which catalyzes the final reaction of glycogenolysis and allows glucose transporters to release glucose inside the cell (ibid.). Therefore, specific muscle glycogen stores to be utilized in running must be “replenished” before the run (Rapoport, 2010; Rodriguez et al., 2009).

To some extent, during the training process for endurance development, the internal factors can be influenced through adaptation to training loads (Booth & Thomason, 1991; Papić et al., 2023), which can result in improved performance for runners (Papić et al., 2019; Seiler & Kjerland, 2006). According to some authors, four weeks of high-intensity interval training (*HIIT*) can improve running economy and maximum achieved speed but not pacing strategy and overall performance (Silva et al., 2017). As running speed decreases with reduced stride length and/or frequency, local muscular endurance can be considered a key factor in sustaining these two kinematic parameters during a race (Hanley et al., 2011). Strength training programs, in addition to adaptations to running training at different intensities, can also offer a powerful stimulus to counter fatigue during the latter parts of a 10 km race, resulting in improved overall performance (Damasceno et al., 2015). Additionally, certain external factors that impact performance, such as footwear, clothing, nutrition and hydration, warm-up, running pace strategy and others can be adjusted during the actual competition. A recent study suggested that the intensity of warm-up can significantly influence performance outcomes. The authors concluded that a high-intensity warm-up may be associated with better lactate threshold and 5 km race results (Alves et al., 2023). In practice, warm-up for long-distance races is generally performed at a low intensity (García-Pinillos et al., 2019), which may be suitable for half-marathons and marathons, where the intensity is lower compared to a 5 km race. However, the study by Alves et al. (2023) highlights the need for further research on the impact of high-intensity warm-ups on performance in these two longer distances.

Many studies highlight the significance of pacing strategy in long-distance running (Foster et al., 2023; Kais et al., 2019; Skorski & Abbiss, 2017; Smyth, 2018; Venturini & Giallauria, 2022). The authors have all found that pacing strategy is a key factor influencing performance. The following text provides a more detailed description of the concept and significance of PS in long-distance running.

1.2. The Concept and Significance of Pacing Strategy in Long-Distance Running

Some definitions indicate that pacing strategy (PS) encompasses the distribution of energy reserves, strength, and speed throughout the entirety of a race without significant deceleration (Baron et al., 2011; Tucker & Noakes, 2009), or, in other words, the distribution of effort intensity during a race. It can be said that the decision on a current pace in a race is an integration of anticipation, knowledge of the finish line, previous experience, and sensory feedback received by the runner (Foster et al., 2023; Skorski & Abbiss, 2017; St Clair Gibson et al., 2006). The most important factors in establishing PS are the distance or duration of a race, that is, the knowledge of where the finish line is (St Clair Gibson et al., 2006). The teleoanticipatory center of the brain incorporates information about the race distance into an algorithm, along with previous experience, current external conditions, internal metabolic functions, and energy reserves (ibid.). The teleoanticipation model was conceived as a feedback-driven, closed-loop system that anticipates and regulates energetic output (Foster et al., 2023). Based on this, an output power is established that allows the runner to reach the end of a race at the highest possible speed without causing total exhaustion in any physiological system. Such exhaustion can occur during a race if the chosen speed is too high at any point (St Clair Gibson et al., 2006).

Factors that significantly influence PS include the depletion of glycogen stores, thermoregulation, neuromuscular fatigue, and an increased rating of perceived exertion (*RPE*) (Foster et al., 2023). It is crucial for athletes to avoid complete exhaustion before reaching the finish line (Skorski & Abbiss, 2017; St Clair Gibson et al., 2006), commonly known as “hitting the wall” in marathon running. From a physiological perspective, the “wall” is defined as the moment when glycogen stores are depleted (hypoglycemia), and the body must rely on fat as the energy source (Stevinson & Biddle, 1998). The availability of “fuel” becomes a problem if the race lasts longer than approximately two hours (Impey et al., 2020; Joyner & Coyle, 2008). At that point, the glycogen content in skeletal muscles becomes depleted, and the limited ability of active muscles to take up glucose from the blood (via the liver or food intake) can limit the rate of oxidative ATP production and subsequently impact the sustainable pace (Joyner & Coyle, 2008). It is estimated that around as many as 43% of runners experience this condition during a marathon race, resulting in a significant decrease in pace (Berndsen, Lawlor, et al., 2020; Buman et al., 2008; Smyth, 2021), or a sudden and painful decline in performance (Rapoport, 2010). Various factors contribute to this phenomenon, including weather conditions, inadequate hydration strategies, and poor pacing decisions (Berndsen, Lawlor, et al., 2020). However, recent recommendations for avoiding “hitting the wall” emphasize the importance of pacing strategy, focusing primarily on PS recommendations (Berndsen, Smyth, & Lawlor, 2019, 2020), highlighting the importance of this controllable factor.

In addition to hypoglycemia, the onset of hyperthermia resulting from muscle glycogen depletion is another mechanism that can influence pacing in long-distance running (Billat, 2005; Coyle, 2007). As body temperature rises, a decline in pace is often observed once it reaches approximately 39 °C (Rodrigues Júnior et al., 2020). Increased humidity has been found to correlate with improved running speed (Weiss et al., 2022).

PS plays a crucial role in preventing intolerable homeostatic disturbances (heart rate, blood lactate, RPE, and muscle O_2 saturation) during a race (Foster et al., 2023; Koning et al., 2011; Tucker & Noakes, 2009). A key requirement for successful PS is the intricate balance between achieving optimal performance and sustaining tolerable homeostasis (Abbiss & Laursen, 2008; Foster et al., 2023; Tucker et al., 2006). This balancing system entails considerations of energy availability, technique, and fatigue (Foster et al., 2023). Good pacing significantly reduces the risk of a cardiovascular drift, which manifests as an increase in heart rate at the same intensity during prolonged physical activity (Billat et al., 2020). It also reduces the risk of musculoskeletal injuries

(Koning et al., 2011) and makes the race more enjoyable for recreational runners (Cuk, Nikolaidis, & Knechtle, 2019).

In conclusion, it is evident from the information provided that PS plays a pivotal role in determining the performance of long-distance running (De Leeuw et al., 2018; Edwards & Polman, 2013; Kais et al., 2019; Renfree & St Clair Gibson, 2013; Skorski & Abbiss, 2017; Thiel et al., 2012). The types of pacing strategies in these disciplines will be analyzed further in the text.

1.3. Types of Pacing Strategies in Long-Distance Running

The optimal PS depends on several factors, including the duration of an event, power output decline (Abbiss & Laursen, 2008; Tucker, 2009; Tucker & Noakes, 2009), knowledge, experience (Deaner et al., 2015; Swain et al., 2020), and the athlete's physiological capacity (Nikolaidis & Knechtle, 2018b; St Clair Gibson et al., 2006). St Clair Gibson et al. (2006) suggested that the overall PS should be determined at the beginning of the race, while continuously adjusting the pace throughout the race to accommodate unexpected changes in the external environment and internal physiological responses. This adaptive approach ensures that the overall PS is maintained.

The most commonly observed PSs during long-distance races include various patterns (Figure 2): even pacing (constant/uniform/consistent – without significant speed changes) (Koning et al., 2011; Pryor et al., 2020), positive pacing (gradually decreasing speed, also known as positive split), negative pacing (gradually increasing speed, also known as negative split) (Koning et al., 2011; Pryor et al., 2020), variable pacing (with multiple significant changes in speed) (ibid.), terrain-dependent pacing (Pryor et al., 2020), reverse J-shaped parabolic pacing (positive with an end spurt) (Abbiss & Laursen, 2008; *INEOS 1:59 Challenge*, 2023; Nikolaidis & Knechtle, 2018a, 2018b), and U-shaped parabolic pacing (faster start and finish compared to the middle section of the race) (Abbiss & Laursen, 2008; Casado et al., 2021).

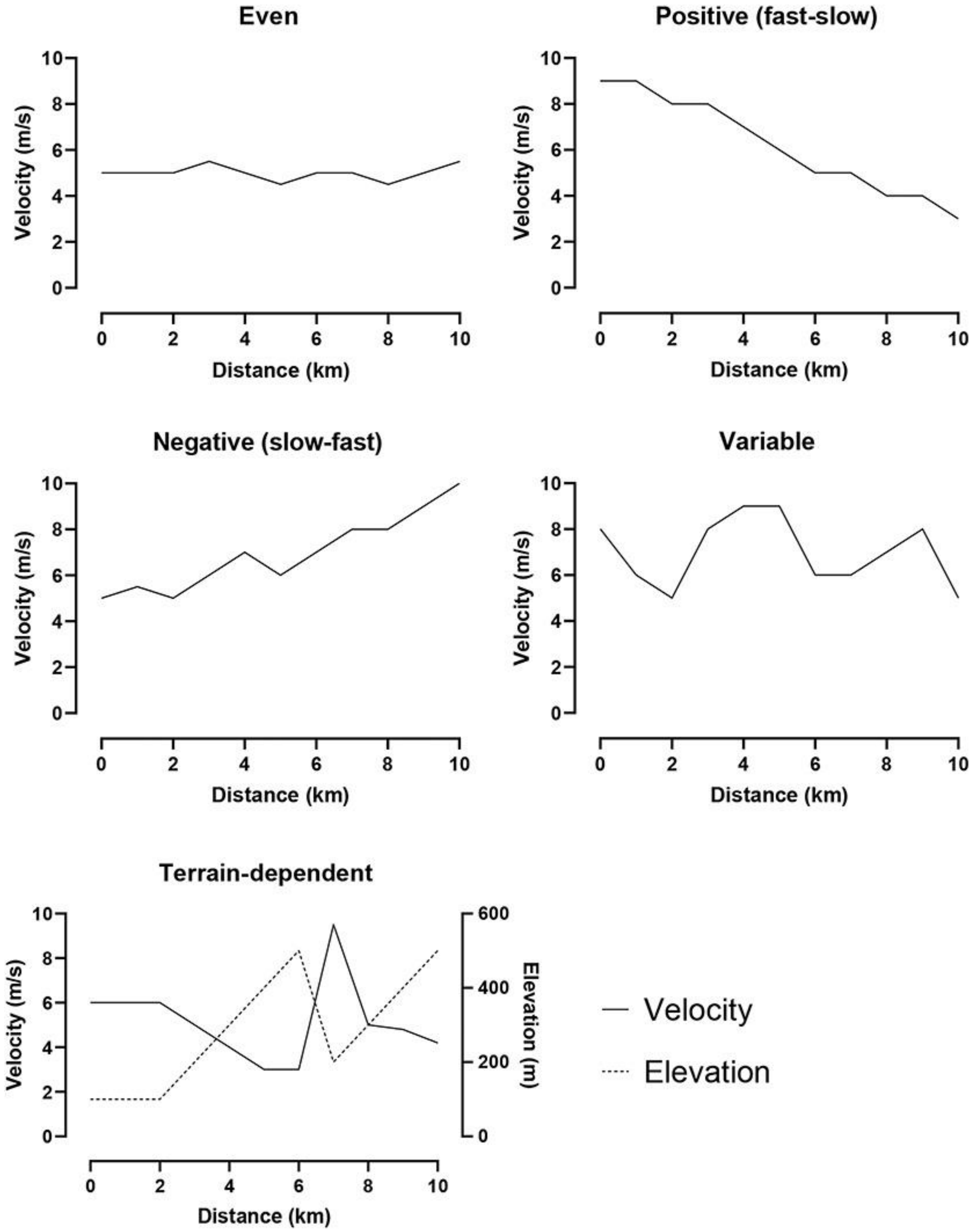


Figure 2. Types of running pacing strategies (Pryor et al., 2020).

A recent study conducted on elite marathon runners revealed that even small increases in pace variation over five-kilometer segments had a significant negative impact on overall race time, with a 1-minute increase in pace variation resulting in a 6.75-minute slowdown (Leslie et al., 2023). The study also found that reducing pace variation helped mitigate the effects of external heat stress on the runners, which led the authors to recommend maintaining an even pace for achieving the best possible results in the race (ibid.). It may be argued that sustaining an even pace is the most efficient metabolic strategy for completing long-distance races in any given situation (Rapoport, 2010). The level of effort exerted by the runner (*% VO_2max*), which can be estimated through mechanical parameters such as critical power (Ruiz-Alias et al., 2022), or critical speed (Pettitt, 2016), is a critical parameter. While the concept of critical power and work capacity above it (*W*') is well-known in cycling (Chorley & Lamb, 2020; Karsten et al., 2015; Poole et al., 2016), it has also been applied to the training of runners in recent years, with the aid of wearable devices for measuring various parameters during running (Imbach et al., 2020; Ruiz-Alias et al., 2022). Critical power represents a mechanical parameter closely related to the physiological threshold at which a metabolic disturbance occurs (*Respiratory Compensation Point – RCP*), and it can be determined in a simple and accessible way using small and lightweight devices attached to shoelaces (Ruiz-Alias et al., 2022). This parameter integrates respiratory, metabolic, and contractile factors within a coherent framework, separating the intensity of activity at which the organism's physiological response can be stabilized from the intensity at which it cannot reach a stable state (Keir et al., 2015; Poole et al., 2016). By knowing their critical power value, runners can better predict, monitor, and control their current and overall effort levels during training and competition (Ruiz-Alias et al., 2022, 2024). Considering that pace depends on a gradient when running on variable terrain, critical power emerges as a more reliable parameter for monitoring and controlling effort levels compared to running pace. However, on a constant flat track, effort level tends to be roughly proportional to running pace (Rapoport, 2010). The following text mentions numerous studies that have examined different PSs in running.

In a positive PS, a decrease in intensity can potentially result from increased glycogen depletion, leading to altered substrate utilization, neuromuscular fatigue, and/or psychological factors associated with individual perception of fatigue (Abbiss & Laursen, 2008). Additionally, one of the causes of progressive decline in marathon running speed is the development of moderate to large muscle damage caused by running (Del Coso et al., 2017), which may be associated with the occurrence of muscle cramps during or immediately after a race (Martínez-Navarro et al., 2022). From a biomechanical perspective, significant speed reduction during a race occurs due to changes in running kinematics, namely reduced stride length and cadence (Girard et al., 2013; Hanley et al., 2011), while ground contact time and total step duration increase (Girard et al., 2013). However, no significant changes in joint angles or foot positioning at initial ground contact during the race have been observed (Hanley et al., 2011). The decline in speed can also be explained by a hazard score, which indicates a homeostatic disturbance calculated as the product of the current subjective RPE and the remaining part of the race (Koning et al., 2011; Piacentini et al., 2019). Some authors suggest that PSs in recreational runners are initially guided by the perceptual factor (RPE), followed by muscle and physiological factors in the middle and final stages of the race (Bertuzzi et al., 2014). Increased cognitive load can also negatively affect the pace of a 5 km race (McCarron et al., 2013). The prefrontal brain region is thought to play a role in regulating pace during solo running (ibid.).

Some studies suggest that negative PS may be most appropriate for long-duration activities such as marathons, as it is associated with decreased carbohydrate utilization, lower oxygen consumption, and lower blood lactate concentrations (Abbiss & Laursen, 2008; Hanley, 2014). As the distance of the race increases, result-achieving tactics become less important compared to efficient energy management, and PS plays a crucial role in that (Filipas et al., 2021).

A variable PS is not a metabolically efficient solution for running long distances on courses with relatively small changes in terrain gradient (Rapoport, 2010). The proportional contribution of carbohydrates in the metabolic fuel mix utilized by a given runner increases supra-linearly with intensity, i.e., running speed (Figure 1). When a runner aims to complete a race within a specific time and distance, they must maintain a certain overall average pace throughout (ibid.). If they fall below this target pace at any time interval, they need to compensate by running faster than the average pace later on to achieve the desired overall average speed by the end of the race. During the slower intervals, carbohydrate utilization decreases compared to what it would be if the target pace was maintained (ibid.). However, during the compensatory, faster interval, not only does carbohydrate utilization exceed what it would be if the target pace was maintained, but it also surpasses the carbohydrate savings achieved during the slow interval (ibid.). As a result, the net carbohydrate utilization is greater than it would be if there were no variation from the target running pace (ibid.), indicating that this type of pacing is not metabolically efficient.

The reverse J-shaped parabolic PS has characteristics similar to positive pacing, with the distinct feature of a pronounced acceleration in the final section of the race (*end spurt – ES*) (Abbiss & Laursen, 2008). This pronounced final acceleration reflects a cautious approach and the preservation of energy reserves throughout the race to avoid complete exhaustion before reaching the finish line (Koning et al., 2011; Smyth, 2018). By maintaining an energy reserve, runners can tap into it during the final stretch of the race, resulting in the observed ES.

On the other hand, the U-shaped PS involves starting the race at a faster pace, followed by a gradual decline in speed during a race, and then a reacceleration in the later part of a race, often accompanied by a strong ES (Abbiss & Laursen, 2008). In other words, it exhibits a positive-to-negative pacing pattern (ibid.). This PS is more efficient for distances where tactical considerations play a significant role, such as in a 5 km race, where it is common for runners to aim for a good initial position within the group and then utilize a fast finishing kick to secure a strong overall performance (Casado et al., 2021).

2. PREVIOUS RESEARCH

Previous research has indicated that there are variations in PSs among different long-distance running disciplines (De Leeuw et al., 2018; Filipas et al., 2021; Menting et al., 2021). It is widely recognized that pacing plays a significant role in running performance, with factors such as performance level, sex and age associated with pacing patterns (Kais et al., 2019; Nikolaidis & Knechtle, 2019). Consequently, analyses of road races (outside the track) have been conducted, taking into account factors such as performance level and/or sex and/or age in disciplines such as marathon (Hernando et al., 2020; Kais et al., 2019; Muñoz-Pérez et al., 2020; Pycke & Billat, 2022), half-marathon (Hanley, 2015; Stanković et al., 2019), 10 km races (De Leeuw et al., 2018; Lima-Silva et al., 2010), ultramarathon (Chatzakis et al., 2021; Deusch et al., 2021; Knechtle et al., 2022; Suter et al., 2020) and triathlon (Knechtle, Käch, et al., 2019). Since the marathon is the only running discipline in athletics held outside the track and included in the Olympic Games, it has been extensively studied with regard to PSs based on all three factors (performance level, sex and age) (Kais et al., 2019; Muñoz-Pérez et al., 2020; Nikolaidis & Knechtle, 2017; Pycke & Billat, 2022; Stojiljković et al., 2020).

Over the past 50 years, the PSs of the world's top marathon runners have undergone changes (Díaz et al., 2018). From 1967 to 1988, athletes started the race at a pace faster than the target pace required to break the world record and slowed down significantly in the final kilometers (ibid.). However, since 1988, there has been a shift from positive pacing to negative pacing, with athletes now covering the initial kilometers of the marathon at a very consistent pace (relatively slower than earlier athletes) and then accelerating from the 25th km towards the finish line (ibid.).

In recent decades, there has been a significant increase in the number of runners participating in running disciplines outside of the athletic track, but the largest number of races and participants worldwide is recorded in 5 km, 10 km, half-marathon, and marathon races (Anthony et al., 2014; *Dubai Fitness Challenge*, 2022; *World's Marathons*, 2021; Knechtle et al., 2016; Nikolaidis et al., 2021; Vitti et al., 2020). Among these races, the half-marathon may have the highest number of participants based on annual races and participants (Knechtle et al., 2016). There has been a significant growth trend in the number of female participants compared to male participants in these disciplines (Lepers & Cattagni, 2012; Stojiljković et al., 2019; Yang et al., 2022). Additionally, there has been a noticeable increase in participation among older age groups (>40 years) compared to younger age groups (Lepers & Cattagni, 2012). The number of male participants is always higher than the number of female participants in all races, but this ratio is smaller in shorter long-distance races and increases with the length of a race (10 km = 0.6; half-marathon = 1.45; marathon = 3.86) (Nikolaidis et al., 2021). As the race distance increases, there is a smaller proportion of female runners (Nikolaidis et al., 2021). In 2022, there were over 193,000 participants in a 5 km race in Dubai, setting a world record for the highest number of participants in a long-distance running event (*Dubai Fitness Challenge*, 2022). While races of this distance are highly popular among recreational runners, there is limited research examining PSs in this particular discipline due to the absence of official split times.

2.1. Running Pacing Strategy Based on Performance Level

2.1.1. 5K Race

Previous research has primarily focused on analyzing PSs in the 5 km running distance investigating their relationship with various factors such as physiological factors (Gosztyla et al., 2006), biomechanical factors (Girard et al., 2013; Hanley et al., 2011), and cognitive factors (McCarron et al., 2013) separately for male and female runners. These studies were conducted on a small sample of participants, mostly under laboratory conditions and on an athletic track. The athletic track, with its unique surface and 400 m loop featuring curves, serves as the primary venue for professional athletes, distinguishing it from off-track running environments. There is only one study, also with a small sample size, that specifically analyzed the PS in a street race of 5 km distance among high-level performance athletes and elite athletes of both sexes (Hanley et al., 2011). Two studies examined the PS in the 5,000 m running discipline based on the performance of participants in major competitions (Filipas et al., 2021) and young elite runners (Menting et al., 2021), but none of these studies considered differences in sex and age.

Based on previous research, the most common observed PS pattern is a U-shaped parabolic curve (Casado et al., 2021; Girard et al., 2013) which is associated with better performance outcomes (Tucker et al., 2006). In this discipline, tactics such as running in a group and securing a good position at the beginning of the race are important, resulting in a faster start and finish (Filipas et al., 2021; Girard et al., 2013; Menting et al., 2021). This trend of a faster start compared to planned even pacing is observed among both female participants of intermediate performance level (Gosztyla et al., 2006) and male participants (Alves et al., 2023; Girard et al., 2013; Lima-Silva et al., 2012). A start like this has also been observed in elite runners of both sexes during a street race of 5 km distance (Hanley et al., 2011). A faster start compared to an even or negative split pace is also recommended for achieving better performance in middle-distance races (Aisbett et al., 2009). However, when measuring split times at 1,000 m intervals in medal-winning athletes at major competitions, a clear negative PS pattern is evident (Filipas et al., 2021). Among less successful male runners, there is a less pronounced ES and falling behind the leading group toward the end of the race. In contrast, less successful female runners fall behind the leading group much earlier, with a slight decline in speed in the second half of the race (ibid.). It can be assumed that less successful female runners have a better PS compared to less successful male runners because they more realistically assess their abilities and stick to the planned race pace instead of chasing a pace beyond their capabilities (Allen & Dechow, 2023). In the same 5 km distance among runners under 20 years of age at the World Championships, a significant correlation between PS and performance is observed (Menting et al., 2021). Medalists start the race at a faster pace, then slightly slow down and accelerate again in the second half (women) or the last 1,000 m of the race (men), reaching a speed higher than at the beginning of the race (ibid.). This PS resembles a J-shaped profile, while less successful runners show a greater decline in speed from the start and a less pronounced ES (ibid.).

The 5 km distance offers advantages for measurement and assessment in research settings, as it allows for direct measurement and multiple testing sessions with appropriate rest periods of several days between tests (Lima-Silva et al., 2012). This makes it easier to directly measure and/or assess the influence of various factors. However, as the distance increases, conducting such analysis becomes more challenging due to excessive fatigue, requiring longer recovery periods. In one study, higher training volume, higher VO_2peak, higher maximal treadmill running speed, and better performance in the 5 km race resulted in a smaller decline in running speed during the race (Nummela et al., 2008).

Despite the global popularity of the 5 km distance, there is a lack of publicly available data on split times during races in mass events held outside of athletic tracks, making it impossible to analyze large samples of participants. As a result, research has mainly been conducted in experimental conditions and on an athletic track, making it difficult to obtain reliable data with subcategories based on performance, sex, and age that would fully reflect real-world race scenarios. Future research should strive to collect data from diverse populations in actual 5 km road races to provide more comprehensive insights into pace strategies based on different factors.

2.1.2. 10K Race

A small number of studies have examined the PS in 10 km races based on performance level, mostly among highly trained runners. In a 10 km race (off-track), negative, even, and positive PS patterns were observed, with even pacing being the most common among runners with higher performance levels (De Leeuw et al., 2018). In a 10,000 m race (on an athletics track), both higher and lower performance groups followed a classic U-shaped PS pattern (Damasceno et al., 2011; Lima-Silva et al., 2010), where runners started faster than the average pace, gradually slowed down, and then accelerated again towards the end (Lima-Silva et al., 2010). However, runners with lower performance exhibited a more consistent pace compared to those with higher performance, with a less pronounced fast start compared to the average speed they achieved in the race. Elite runners from major competitions showed a slightly different PS pattern. They exhibited an even pace and substantial ES, both among male and female runners (Filipas et al., 2021). Slower starts and negative PSs were observed in runners with the best performance, followed by an even pace in those with slightly lower rankings, and positive PSs in those with the lowest performance (Filipas et al., 2021). Unlike the 5,000 m race where tactics play a significant role, energy management is crucial in the 10,000 m race (Filipas et al., 2021). Among young male runners (below 20 years of age) who won medals in major competitions, a slightly negative PS with a smaller ES was also observed, while runners with lower performance demonstrated a positive PS with a greater ES (Menting et al., 2021).

2.1.3. Half-Marathon

There are very few studies that have examined the PS in a half-marathon based on performance level (De Leeuw et al., 2018; Hanley, 2015). Among runners with a high-performance level, slightly negative and positive PSs were observed (De Leeuw et al., 2018), while elite runners tend to exhibit a parabolic reverse J-shaped PS (Hanley, 2015). Most runners finished the first 5 km segment relatively quickly, progressively slowed down until around the 20 km mark, and then significantly accelerated during the final 1.1 km segment (Hanley, 2015). Additionally, a smaller decline in pace was observed among runners who ran in a group during the race (ibid.). Although running in a group may lead to a smaller decline in pace after the fifth kilometer, it is important for athletes to be cautious and not join a group with a pace that is too fast for their capabilities (ibid.).

2.1.4. Marathon

A number of studies have examined the PS based on performance levels in different marathon races (Kais et al., 2019; Muñoz-Pérez et al., 2020; Pycke & Billat, 2022; Santos-Lozano et al., 2014; Stojiljković et al., 2020). Marathon running is typically associated with positive pacing, but faster athletes demonstrate the least decline in speed (De Leeuw et al., 2018; Hubble & Zhao, 2016; Kais et al., 2019; Renfree & St Clair Gibson, 2013; Santos-Lozano et al., 2014; Stojiljković et al., 2020). Slower runners start significantly faster than their average speed within the first 20–25 km, after which their running speed decreases significantly below the average speed of the entire race (Santos-Lozano et al., 2014; Stojiljković et al., 2020). In a study by Stojiljković et al. (2020), on a total sample of 937 runners who completed the Belgrade Marathon in 2019, a significant difference in PSs was observed among the four performance-level groups. Elite and well-trained marathon runners generally maintain an even pace throughout the race (Muñoz-Pérez et al., 2020). Both male and female medallists in World Championships and Olympic Games generally ran the marathon with an even pace from the 10th kilometer onwards, while those who finished slightly slower dropped out of the leading group at approximately the halfway point (Hanley, 2016). Running with a group of runners with similar performance levels has proven to be more efficient than running alone (Hanley, 2015, 2016).

Based on the analyzed studies utilizing data from mass participation events, it can be concluded that runners with higher performance levels exhibited a more evenly distributed PS compared to runners with lower performance levels (Chatzakis et al., 2021; Kais et al., 2019; Nikolaidis & Knechtle, 2017; Santos-Lozano et al., 2014).

2.2. Running Pacing Strategy Based on Sex

2.2.1. 10K Race

Significant differences between male and female runners in the 10,000 m race on the athletics track have been found among elite runners (Borba et al., 2021). Male runners slowed down after the first kilometer and maintained a stable pace until the ninth kilometer, after which they accelerated again (ibid.). Female runners increased their running speed towards the second kilometer and maintained the pace until the ninth kilometer, with the tenth kilometer being faster (ibid.). However, female runners also showed a higher average variation in speed compared to male runners (ibid.). Only one study examined the PS in a 10K race outside the athletics track and compared it with the PS in the marathon (Cuk et al., 2021). Detailed comparisons of PSs at different distances are covered in a separate chapter of this research.

2.2.2. Half-Marathon

According to available data, only one study compared the PS between elite male and female runners in the half-marathon (Stanković et al., 2019). In the study, among the top 50 male finishers in the Vienna Half-Marathon, a significant pace decline was observed after the first 5 km, while the top 50 female finishers had a better and more evenly distributed PS than male finishers. However, a decline in pace was observed in both sexes as the race progressed. A significant difference in PS between sexes was found only between the 10 km and 15 km marks (in the third segment, where women ran relatively faster than men), followed by a sharp decrease in running pace from the 15th kilometer until the end of the race.

Two other studies examining sex differences in PS among recreational runners in the half-marathon have also compared it with the marathon (Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis, Ćuk, & Knechtle, 2019). A separate chapter was dedicated to comparing the PS between these two distances.

2.2.3. Marathon

In general, men run faster than women by about 10–20% depending on the race distance (Knechtle & Nikolaidis, 2022; Nikolaidis et al., 2017). However, with the increasing number of participants in races, there has been a decline in the average marathon running pace over the years (Reusser et al., 2021; Stojiljković et al., 2022), particularly among male runners (Lepers & Cattagni, 2012). As a result, the difference in average results between male and female runners has been reduced (ibid.). Additionally, there has been a greater increase in the number of women participating in these races compared to men (Lepers & Cattagni, 2012; Stojiljković et al., 2019). Previous research reported significant differences in marathon PSs between the sexes (Kais et al., 2019; Stojiljković et al., 2020) among non-elite runners, with the difference being more pronounced at higher external temperatures (Trubee et al., 2014). Other authors have not observed significant differences in PSs among elite runners (Trubee et al., 2014). A positive PS has been observed in both sexes regardless of performance level (Breen et al., 2018; De Leeuw et al., 2018; Kais et al., 2019), except for world record holders (Díaz et al., 2019). However, recreational female runners have been found to start the race more conservatively, maintain a more stable pace throughout the marathon, and experience less decline in running pace in the final part of the race (De Leeuw et al., 2018; Hernando et al., 2020; Hubble & Zhao, 2016; March et al., 2011; Stojiljković et al., 2020). One study found that women ran up to 4.5% faster than men in the final kilometers (from the 40th km to the finish line) (Hernando et al., 2020). It can be assumed that male runners overestimate their abilities at the beginning of the race, leading to a significant decline in pace during the race. Therefore, overconfidence may be one of the psychological factors partially explaining poorer PS in male runners (Hubble & Zhao, 2016). However, even elite female runners with relatively poorer performances have been found to start the race at a pace too fast compared to their abilities, possibly due to following the pace set by better-performing athletes (Renfree & St Clair Gibson, 2013). Similar findings have been observed in elite men at the World Cross Country Championships (Hanley, 2014). When comparing male and female marathoners in the same performance groups, the pace decline in male runners is significantly more pronounced in the group with finishing times ranging from 2:15 h:min to 2:30 h:min, and all performance groups from 3 to 6 hours (Kais et al., 2019). A significant difference between sexes was observed in the 25–30 km segment (Nikolaidis & Knechtle, 2018a). However, a negative (Díaz et al., 2019) and even PS with acceleration at the end (Muñoz-Pérez et al., 2023) were observed in male world record holders in the marathon, while women's PSs were less consistent (Díaz et al., 2019) and negative with an ES among the medal winners (Hanley, 2016).

2.3. Running Pacing Strategy Based on Age

Studies that examined running pacing in 10 km and half-marathon races according to age also investigated marathon PS and compared pace across these different distances. The comparison between running PSs at different distances is covered in a separate chapter. Given the large number of runners and the increasing trend of participants in all age categories in these disciplines, further research on this issue is important.

2.3.1. Marathon

Since 1980, there has been a notable increase in marathon participants in the master categories (>40 years) in both men and women (Lepers & Cattagni, 2012), which could be attributed to older runners being more emotionally stable and responsible compared to younger individuals (García-Naveira et al., 2011). The highest number of participants has been recorded in the 30–39 age category, both globally and in our country (Lepers & Cattagni, 2012; Stojiljković et al., 2019). This data can be associated with factors such as physical needs, social influences and available time (Anthony et al., 2014).

Previous research indicates significant differences in running PS among different age categories (Kais et al., 2019; March et al., 2011; Nikolaidis & Knechtle, 2017). Both male and female runners in all age categories tend to decrease their running pace during a marathon (positive pacing) and show an ES (40–42.2km) (Nikolaidis & Knechtle, 2018a). In other words, the 5–10 km segment was the fastest, while the 35–40km segment was the slowest (Nikolaidis & Knechtle, 2017, 2018a, 2019). Older runners exhibited a more evenly distributed pace compared to younger runners with similar performance levels (Kais et al., 2019; March et al., 2011; Nikolaidis & Knechtle, 2017) with a more pronounced difference observed among groups with lower performance levels (Nikolaidis & Knechtle, 2017). Veterans (40 years and older) had a 0.05% smaller difference between the first and second half of the marathon compared to non-veterans when controlled for performance level and sex (Kais et al., 2019). However, some studies indicate trivial differences in running PS between different age categories (Nikolaidis & Knechtle, 2018a, 2019).

2.4. Comparison of Running Pacing Strategy between Races of Different Distances

The importance of comparing PS between different long-distance races first emerged due to a lack of answers regarding the mechanism that causes a significant decrease in running speed during the second half of an event (i.e., positive split). Various authors have previously proposed physiological, biomechanical, and psychological mechanisms as potential causes (Coyle, 2007; Deaner et al., 2015; Muñoz-Pérez et al., 2020; Nikolaidis & Knechtle, 2018b; Roelands et al., 2013). Since external conditions can influence PS (El Helou et al., 2012; Trubee et al., 2014), it is beneficial to compare PS under similar external conditions.

In recent years, a new methodological approach has enabled researchers to provide answers by directly comparing PS between different races held in the same event, on the same day, at the same time, and on similar tracks (Cuk et al., 2021; Cuk, Nikolaidis, & Knechtle, 2019; Cuk et al., 2019; Nikolaidis et al., 2019). For example, one study examined the PS between the marathon and the 10 km race (Oslo 2015–2018) based on sex and age (Cuk et al., 2021). In this study, PSs were analyzed based only on the first and second halves of the race. Both 10 km and marathon runners exhibited a positive PS but with a significantly smaller decrease in speed observed in the 10 km race. Female runners displayed significantly less variation in pace compared to male runners in the marathon, while no significant difference between sexes was observed in the 10 km race. A smaller pace variability was noted in the 10 km race compared to the marathon across all age categories. Additionally, the youngest and oldest runners exhibited greater pace variability compared to other age categories in both races. Since in mass participation road races split times are measured at every 5 km, it complicates a more detailed analysis of PS in the 10 km race, restricting the analysis to only two segments. Furthermore, the 10 km race course is rarely within a half-marathon or marathon course, making it difficult to compare it with other races held at the same time, on a large sample of participants, and under similar external conditions. Analysing a large sample is further hindered by the challenge of finding a race with a multi-year tradition that accommodates a large number of participants and include a 10 km course within a half marathon or marathon track. For these reasons, the 10 km race is not further considered in the text.

Other studies using same methodology have directly compared PS between the half-marathons and marathons held in the same event (Vienna and Ljubljana 2017) (Cuk, Nikolaidis, & Knechtle, 2019; Cuk et al., 2019; Nikolaidis et al., 2019). The analysis of PS was conducted based on sex (Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis, Ćuk, & Knechtle, 2019) and age groups (Cuk et al., 2019; Nikolaidis et al., 2019), while no study examined PS between the half-marathon and marathon based on performance level.

In both the half-marathon and marathon races, a decrease in running speed (positive split) during the race was observed for both sexes and across all age categories, with a characteristic ES observed in marathon runners (Nikolaidis et al., 2019). In one study, an ES was recorded in a half-marathon (Cuk et al., 2019), while in other studies it was not observed (Nikolaidis et al., 2019; Nikolaidis, Ćuk, & Knechtle, 2019). Moreover, in both sexes and most age categories, pacing in the half-marathon was found to be more evenly distributed compared to the marathon (Cuk, Nikolaidis, & Knechtle, 2019; Cuk et al., 2019; Nikolaidis et al., 2019; Nikolaidis, Ćuk, & Knechtle, 2019).

In longer races and among older age groups, there is evidence to suggest that the performance gap between the sexes becomes less pronounced (Nikolaidis et al., 2021; Yang et al., 2022). Results from mass races indicate that the category of female runners in the half-marathon is slower than female runners in the marathon, while the situation is reversed for male runners (Nikolaidis et al., 2019). Since both analyzed races took place on the same day and external conditions could not have had a significant impact on this result for female runners, further analysis is warranted. Considering that the average performance decreases with an increasing number of participants (Reusser et al., 2021; Stojiljković et al., 2022), this result can be attributed to nearly eight times more women participating in the half-marathon compared to the marathon, while there were three times more men in the half-marathon (Nikolaidis et al., 2019). Since the trend of growing women's participation in these races in recent years is greater than that in men (Stojiljković et al., 2019; Yang et al., 2022), it is plausible to assume that a large number of female runners in the half-marathon are beginners. Moreover, the half-marathon race, being a shorter and more accessible distance compared to the marathon race, leads to a well-founded assumption that most beginners are likely to opt for it and consequently achieve poorer results, as evidenced in the study conducted by Nikolaidis et al. (2019). However, some studies indicate that both male and female runners tend to run at a slower pace in the half-marathon compared to the marathon (Yang et al., 2022). Another possible factor contributing to slower running in shorter distances compared to longer ones is the difference in training approaches. Recreational runners preparing for marathons and ultramarathons are more likely to seek professional help during their training compared to those preparing for half-marathons (Knechtle, Tanous, et al., 2021). However, female runners showed a more evenly distributed pace compared to male runners in the marathon, while the pace difference between sexes was almost negligible in the half-marathon races (Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis, Ćuk, & Knechtle, 2019) and 10 km races (Cuk et al., 2021). This trend was also observed in different age categories (Cuk et al., 2019).

The data suggests that the age categories participating in marathons tend to be older than those participating in half-marathons (Yang et al., 2022), particularly in the men's category, while for women, this is not the case (Nikolaidis et al., 2019). The fastest age category in both the half-marathon and marathon distance consists of runners younger than 25 years old, while the slowest category comprises runners above 54 years old (ibid.). This finding differs significantly from the results obtained in a study that examined the performance level of male marathon runners across 10-year age intervals, where the fastest category was 40–50 years old and the slowest category was under 30 years old (Stojiljković et al., 2022). There was no difference in pace variability across age categories for female runners, while male runners younger than 30 years old and older than 60 years old showed greater pace variability compared to other age categories (Cuk et al., 2019). In the same study, younger runners of both sexes in the half-marathon showed the most pronounced ES compared to older age categories and marathon runners.

Only one study simultaneously analyzed the role of PS and sex in races of different distances (10 km, half-marathon, and marathon) with a large sample size (N = 120,472) over three years (De Leeuw et al., 2018). They analyzed split times at each race that were not proportionate to each other. Specifically, the two shorter races had three split times (5 km and 8 km in the race of 10K; and 8 km and 16 km in the half-marathon race), while the marathon had split times recorded at every fifth kilometre. However, this study did not statistically compare the three disciplines based on these factors. Instead, for each discipline, a separate descriptive analysis of PS was performed for male and female runners. Additionally, age groups were not compared to each other. Instead, age was treated as a variable in the prediction equation for race results. The race results were then transformed into relative time (t_{rel}), using the equation $t_{rel} = t/t_{med}(d, g, y)$, where *d* indicated race distance, *g* indicated gender and *y* indicated the year when the race was held.

2.5. Conclusions and Limitations of Previous Research

The following conclusions can be drawn from the existing research:

1. The majority of research on long-distance running PS has focused on the marathon discipline, with a large sample size and considering three factors: performance level, sex and age (Kais et al., 2019; Muñoz-Pérez et al., 2020; Nikolaidis & Knechtle, 2018a; Pycke & Billat, 2022; Stojiljković et al., 2020).
2. Only one study has investigated PS in the half-marathon based on performance level, and only among elite athletes, with a small sample size (Hanley, 2015).
3. Only one study has analyzed PS in the half-marathon based on sex, but focusing on elite runners (Stanković et al., 2019).
4. No study to date has examined PS in the half-marathon based on age.
5. Studies that have used new methodologies have compared the half-marathon and marathon disciplines in a single year, with a relatively small sample size, considering sex and/or age (Vienna and Ljubljana 2017) (Cuk, Nikolaidis, & Knechtle, 2019; Cuk et al., 2019; Nikolaidis, Ćuk, & Knechtle, 2019). However, none of these studies have compared PS in the half-marathon and marathon based on performance level.

Considering the above, there are several limitations in previous research:

1. Insufficient studies, particularly with relatively small sample sizes, have examined PS in the half-marathon, despite being perhaps the most popular race worldwide in terms of the number of races and participants every year (Knechtle et al., 2016; Nikolaidis et al., 2021).

2. Comparisons between half-marathon and marathon PSs have been conducted on relatively small sample sizes, focusing solely on sex and age.
3. No study to date has compared half-marathon and marathon PSs based on performance level.

To address these limitations, it would be valuable to conduct research comparing PSs based on performance level, sex, and age in races of different distances held on the same day. This would provide a clearer understanding of the factors that have the greatest impact on long-distance running PS. As a pilot study for this doctoral thesis, data on PS based on performance levels for half-marathon and marathon runners was published under the title of “The pacing differences in performance levels of marathon and half-marathon runners”.

3. RESEARCH PROBLEM, SUBJECT, AIMS AND TASKS

3.1. Research Problem

The research problem is pacing strategy in half-marathon and marathon runners.

3.2. Subject of Research

The subject of the research is analysis and comparison of pacing strategies in half-marathon and marathon runners, based on performance level, sex and age of runners, in races held under similar external conditions.

3.3. Research Aims and Tasks

Based on the problem and subject of research, the following research aims have been formulated.

Aim 1: Comparison of pacing strategies in half-marathon and marathon runners.

a) Comparison of pacing strategies in half-marathon and marathon runners based on performance level.
b) Comparison of pacing strategies in half-marathon and marathon runners based on sex.
c) Comparison of pacing strategies in half-marathon and marathon runners based on age.

Aim 2: Analysis of pacing strategies in half-marathon runners.

a) Analysis of pacing strategies in half-marathon runners based on performance level.
b) Analysis of pacing strategies in half-marathon runners based on sex.
c) Analysis of pacing strategies in half-marathon runners based on age.

Aim 3: Analysis of pacing strategies in marathon runners.

a) Analysis of pacing strategies in marathon runners based on performance level.
b) Analysis of pacing strategies in marathon runners based on sex.
c) Analysis of pacing strategies in marathon runners based on age.

The research aims will be achieved through the following tasks:

a) Obtaining approval from the Ethics Committee.
b) Collecting publicly available data from the official website of the Vienna Marathon for 17 half-marathon and marathon races (2006–2023 period, except 2020).
c) Cleaning and organizing the collected database.
d) Performing statistical analysis of the data.
e) Interpreting the research findings.

4. RESEARCH HYPOTHESES

Based on the review of previous research and in line with the research aims of this study, the following hypotheses have been defined.

Hypothesis 1: The pacing of half-marathon runners is more evenly distributed compared to the pacing of marathon runners.

a) The pacing of half-marathon runners is more evenly distributed compared to the pacing of marathon runners in all performance groups of both sexes.
b) Female runners pace more evenly compared to male runners in both races, with differences greater in the marathon than in the half-marathon.
c) Middle-aged runners pace more evenly compared to younger and older runners, with differences greater in the marathon than in the half-marathon.

Hypothesis 2: The pacing strategy of half-marathon runners is positive.

a) Higher-performance-level runners of both sexes, pace more evenly compared to runners of lower performance levels in the half-marathon.
b) Female runners pace more evenly compared to male runners in the half-marathon.
c) Middle-aged runners of both sexes pace more evenly compared to younger and older runners in the half-marathon.

Hypothesis 3: The pacing strategy of marathon runners is positive.

a) Higher-performance-level runners of both sexes, pace more evenly compared to runners of lower performance levels in the marathon.
b) Female runners pace more evenly compared to male runners in the marathon.
c) Middle-aged runners of both sexes pace more evenly compared to younger and older runners in the marathon.

5. METHODS

5.1.Research Design

This study was conducted as quasi-experimental research, with an ex-post facto design.

5.2.Sample of Participants

The sample of participants included all runners who completed the Vienna Half-Marathon and Marathon races from 2006 to 2023 (excluding 2020, when races were not held due to COVID-19), based on official data from the Vienna Marathon organizer's website (*Vienna City Marathon*, 2023). A total of 240,696 were initially considered. However, participants with missing data such as sex, age, result in any race segment, final result, and race placement were excluded from the analysis. Additionally, any results in race segments slower than 4.48 km/h, which could even be classified as slow walking (Allen & Dechow, 2023; Dechow & Allen, 2023), and any CS (Change of Speed) and ACS (Absolute Change of Speed) absolute values of 0% or greater than 50%, were excluded from the analysis. The CS and ACS variables will be explained in the following text. Only six participants, with a CS value of 0%, were excluded from the analysis, since this value could not be logarithmically transformed, preventing us from conducting statistical analysis on this data. The 50% threshold was established to mitigate the impact of extreme speed fluctuations (such as transitioning from high-speed running to slow walking, which could indicate excessive fatigue or injury) on pacing. Moreover, in each subcategory for sex, age, and race (total of 24), any "far out" and extreme "out" values identified through SPSS were excluded for logarithmically transformed variables. After the initial data-cleaning process, the final sample comprised 233,083 participants, with 150,232 participants in the half-marathon (men, N = 100,695; women, N = 49,537) and 82,815 participants in the marathon (men, N = 67,118; women, N = 15,697). The sample totaled 167,813 men and 65,234 women.

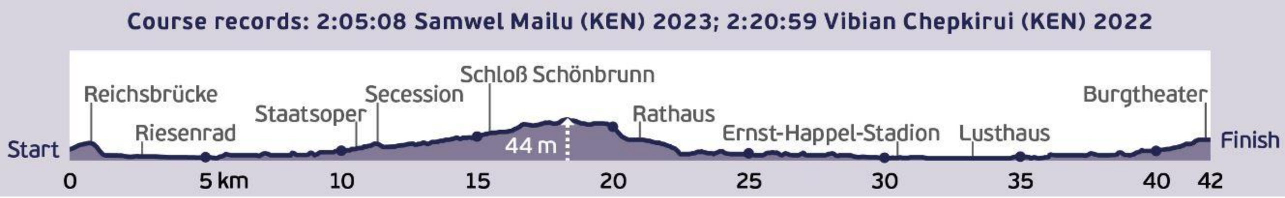
According to the Helsinki Declaration adopted in 1964 and revised in 2013, permission is not required for the use of publicly available data. The present research has obtained the approval of the Ethics Committee at the University of Belgrade – Faculty of Sport and Physical Education. This approval is included as an attachment at the end of this document.

5.3.Race Details

The Vienna Half-Marathon and Marathon usually take place on the same day each year, which is a Sunday in the second half of April at 9 am. However, there were three exceptions: in 2006, it was held in the first week of May; in 2019, it was held in the first week of April; and in 2021, it was delayed until September 12th due to the COVID-19 pandemic. Throughout the entire observed period, both race courses were on an officially certified and fairly flat track with an elevation difference of only 44 meters (Picture 2). For comparison, the Berlin Marathon considered the "fastest marathon" has an elevation difference of 21 m. On October 12, 2019, Eliud Kipchoge completed the marathon distance in 1:59:40.2 h:min:s on a quarter of a standard marathon course, becoming the first person to run a marathon in under two hours (*INEOS 1:59 Challenge*, 2023). Nevertheless, this event took place under circumstances that do not comply with the regulations set by World Athletics (World Athletics Series Regulations, 2023). This fact indicates that the course is flat and fast and adds even more value to this event.

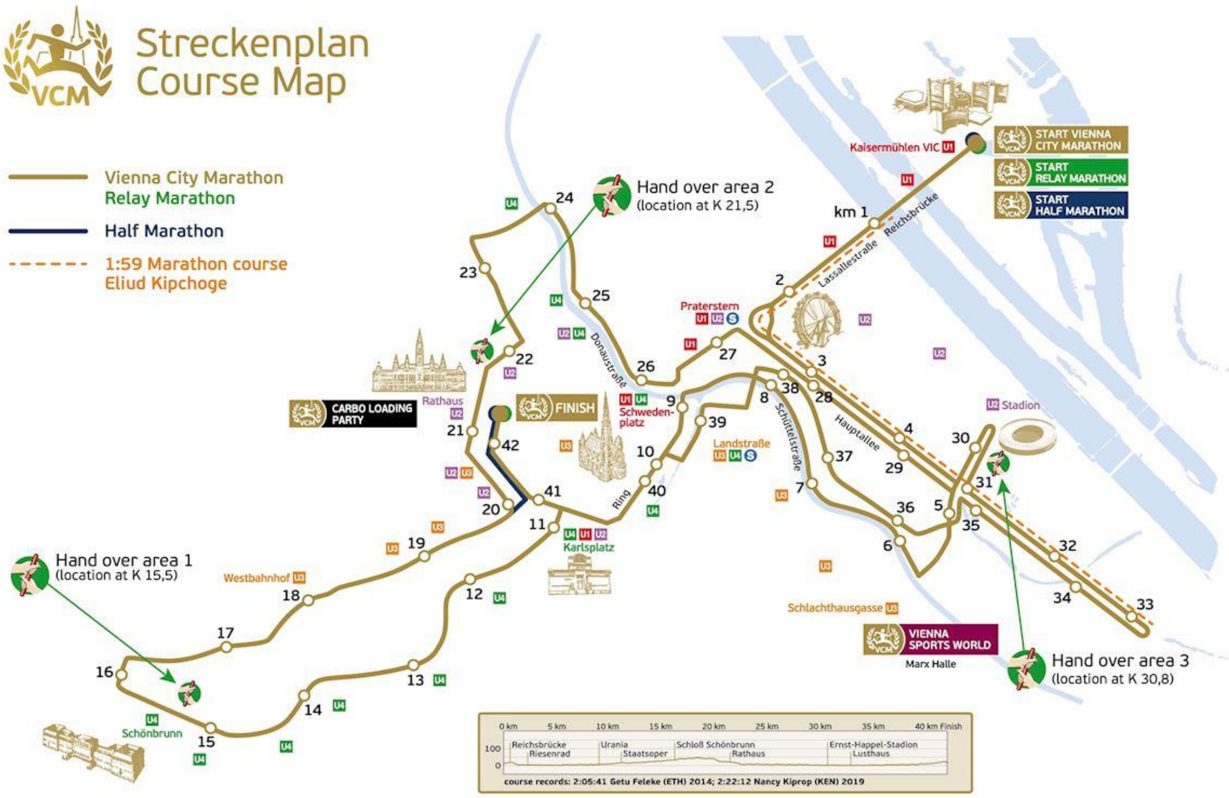
The marathon course encompassed the entire route of the half-marathon (Picture 3) and remained almost identical throughout the analyzed period of 17 years (2006–2023, except 2020). For the research conducted by Ristanović et al. (2023), information regarding the outside temperatures on race days during the period 2006–2018 was retrieved from the official website (*Vienna City*

Marathon, 2021). Throughout the days of the race in this period, the temperature ranged from 7.8 °C (in 2017) to 21 °C (in 2018) at 9 am, and from 10.8 °C (2012 and 2016) to 25.1 °C (in 2018) at 2 pm. Unfortunately, no further details regarding humidity levels or wind speeds were provided on the official race website (*Vienna City Marathon*, 2021). In 2023, the official website of the Vienna City Marathon did not provide any data regarding outside temperatures from previous races (*Vienna City Marathon*, 2023). Therefore, we reached out to the race organizers of the Vienna City Marathon to request the data for the period 2019–2023. They promptly provided us with the precise temperature information for this period, which largely matched the previously mentioned temperatures, except for the year 2021. In 2021, due to the COVID-19 pandemic, the races took place on September 12th and the recorded outside temperature at 2 pm was 25.9 °C, slightly higher than that of 2018.



Picture 2. Terrain configuration of Vienna Half-Marathon and Marathon race course in 2023 (*Vienna City Marathon*, 2024).

Reichsbrücke – the bridge in Vienna; Riesenrad – panoramic wheel for city sightseeing; Staatsoper - State Opera; Secession – exhibition center, Viennese Secession; Schloss Schönbrunn – Schönbrunn Palace; Rathaus – Municipality; Ernst happel Stadion – Football stadium; Lusthaus – House of enjoyment; Burgtheater – theater.



Picture 3. Vienna Half-Marathon and Marathon race course in 2023 (*Vienna City Marathon*, 2023).

5.4.Data Collection and Processing

All data were retrieved from the official Vienna Marathon website (*Vienna City Marathon*, 2023). Initially, race results in terms of overall time, participant details, and an official link to split times for each participant were collected. All these data were transferred to an Excel document. This procedure was done separately for each year, race and sex. Subsequently, split times were added using customized codes in the Python software. These codes extracted split-time data using the official link for each participant.

5.4.1. Dependent Variables

The half-marathon and marathon races were divided into 5 segments each. Race segments were determined based on specific points where split times were recorded during the race and the final time at the finish line. In both races, split times were measured every 5 km using a known chip system on the race bib and gates that record the passing time of each runner. However, to compare split times between races of different distances, we created proportionally equal segments. In the half-marathon, the first four segments were 5 km each, and the fifth segment was 1.0975 km, while in the marathon, each segment was twice the length of those in the half-marathon (Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis et al., 2019; Ristanović et al., 2023). The segments for both races are shown in Table 2.

Table 2. *Race Segments for the Half-Marathon and Marathon Races.*

Race	Segment				
	1	**2**	**3**	**4**	**5**
Half-Marathon	0–5 km	5–10 km	10–15 km	15–20 km	20–21.0975 km
Marathon	0–10 km	10–20 km	20–30 km	30–40 km	40–42.195 km

Then, the average running speed for the entire race and the average running speed for each of the five-race segments were calculated for each half-marathon and marathon participant (Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis, Ćuk, & Knechtle, 2019).

Subsequently, the percentage values of the average change of speed for each of the five segments ($CS_{1–5}$) were calculated relative to the average running speed for the entire race. To calculate the average running speed for the entire race, we divided the race distance by chip time. Then, we transformed all percentage variables to their absolute values (i.e., only positive values were used for statistical analysis and histograms, while both positive and negative values were given in the line graphs). Finally, the absolute change of speed throughout the entire race (ACS) was calculated for each participant as the mean of the 5 CS absolute values (also percentages). This data analysis method has been used before (Cuk, Nikolaidis, & Knechtle, 2019; Knechtle et al., 2022; Nikolaidis et al., 2019). Although speed analysis can also effectively represent PS during the race, one dependent variable – ACS, which represents pace variability, is one of the best choices for a clearer representation of the results (Cuk et al., 2024; Knechtle et al., 2022).

5.4.2. Independent Variables

The first independent variable was performance level. Participants were divided into 24 subcategories based on race, sex, and age group (2x2x6 = 24). Performance levels were calculated within each subcategory. Finally, all the separate databases were merged into a single final database. The high-level group (HL) consisted of the top quartile of the best-placed runners. Then, the moderate-to-high-level group (MHL) was composed of the second-placed quartile. The moderate-to-low-level group (MLL) consisted of the third-placed quartile of participants and the low-level group (LL) consisted of the bottom quartile of participants (Knechtle et al., 2022; Santos-Lozano et al., 2014). The second independent variable was the sex of the participants, namely, male and female runners. The third independent variable was six age groups, each spanning 10 years (except for the youngest and the oldest participants groups, which had a bigger range): 18–29, 30–39, 40–49, 50–59, 60–69, ≥70. Including a wider range of participants from both the youngest and the oldest age groups was necessary to ensure a sufficient number of individuals for a more comprehensive statistical analysis and easier practical data interpretation within these specific categories. Six age groups containing mostly decades were used in other studies (Brisswalter et al., 2014; Leyk et al., 2007; Reusser et al., 2021), although a lot of the studies used mostly 5-year age group intervals (Cuk et al., 2019; Knechtle & Nikolaidis, 2018; Nikolaidis et al., 2019). The fourth independent variable was the race type: half-marathon and marathon.

5.5. Statistical data analysis

First, descriptive statistics were performed to calculate the mean, standard deviation, minimum, and maximum values. Afterwards, the normality of the data distribution was examined using the Kolmogorov-Smirnov test, Shapiro-Wilk test and visually inspecting histograms and q-q plots.

Since all pacing variables were expressed as percentages, before t-tests and all ANOVAs (analysis of variances) were performed, data were log-transformed for the analyses and then back-transformed according to existing methods (Stewart & Hopkins, 2000). Bonferroni's test was used for all post-hoc comparisons. The effect size was represented by eta-squared (η^2) and described using common guidelines: >0.0099 = small effect, >0.0588 = medium effect, >0.1379 = large effect (Cohen, 1988, 284–288). The alpha level was set at $p < 0.05$. All statistical analyses were conducted using Microsoft Office Excel 2019 (*Microsoft Corporation, Redmond, WA, USA*) and IBM SPSS Statistics 20 (*IBM, Armonk, NY, USA*).

5.5.1. Comparison of Pacing Strategies in the Half-Marathon and Marathon

Descriptive statistics were calculated for $CS_{1–5}$ and ACS for the overall sample (both sexes) in the half-marathon and marathon separately. To confirm Hypothesis 1, a mixed between-within subjects ANOVA was conducted to investigate the effect of the race (half-marathon and marathon) on participants' CS in five race segments. Subsequently, an independent-sample t-test was performed to examine the difference in ACS between races.

5.5.1.1. Comparison Based on Performance Level

Descriptive statistics were calculated separately for the half-marathon and marathon, as well as for male and female runners, to determine the average speed of each race segment, average race speed, and ACS for four groups of participants based on performance level. To confirm Hypothesis 1a, a two-way between-groups ANOVA was conducted to investigate the effect of performance level and race (half-marathon and marathon) on ACS (separately for men and women). The same procedure was used to examine the interaction between race and performance level (race × performance level), the main effects of race and the main effects of performance level.

5.5.1.2. Comparison Based on Sex

Descriptive statistics were calculated for the average speed of each race segment, average race speed and ACS separately for male and female runners, as well as for the half-marathon and marathon. To confirm Hypothesis 1b, a two-way between-groups ANOVA was conducted to investigate the effect of sex and race on ACS. The same procedure was used to examine the interaction between race and sex (race × sex), the main effects of race and the main effects of sex.

5.5.1.3. Comparison Based on Age

Descriptive statistics were calculated separately for the half-marathon and marathon, as well as for male and female runners, to determine the average speed of each race segment, average race speed and ACS for age groups. To confirm Hypothesis 1c, a two-way between-groups ANOVA was conducted to investigate the effect of age group and race on ACS (separately for men and women). The same procedure was used to examine the interaction between race and age group (race × age group), the main effects of race and the main effects of age group.

5.5.2. Analysis of Pacing Strategies in the Half-Marathon

Descriptive statistics were calculated for the average speed for each race segment, for the overall sample (both sexes) in the half-marathon. To confirm Hypothesis 2, a repeated measures ANOVA was conducted to examine the difference in average speed between each of the five race segments in the overall sample from the half-marathon.

5.5.2.1. Analysis of Pacing Strategies Based on Performance Level

Descriptive statistics of CS_{1-5} and ACS were calculated separately for male and female runners in four groups of participants based on their performance level in the half-marathon. To confirm Hypothesis 2a, a mixed between-within subjects ANOVA was conducted to examine the influence of performance level on change of speed in the five race segments (separately for men and women). This statistical analysis was used to assess the interaction between segment CS and performance level (segment CS × performance level), the main effects for segment CS (within-subjects factor) and the main effects for performance level (between-subjects factor).

For a more detailed analysis and confirmation of Hypothesis 2a, a two-way between-groups ANOVA was conducted to examine the influence of performance level and sex on ACS. The same procedure was used to investigate the interaction between sex and performance level (sex × performance level), the main effects of sex and the main effects of performance level. In this way we analyzed ACS between male and female runners within each performance group in the half-marathon.

5.5.2.2. Analysis of Pacing Strategies Based on Sex

Descriptive statistics of $CS_{1–5}$ and ACS were calculated separately for male and female participants in the half-marathon. To confirm Hypothesis 2b, a mixed between-within subjects ANOVA was conducted to examine the influence of sex on change of speed in the five race segments. This statistical analysis was used to assess the interaction between segment CS and sex (segment CS × sex), the main effects for a segment CS (within-subjects factor) and the main effects for sex (between-subjects factor).

5.5.2.3. Analysis of Pacing Strategies Based on Age

Descriptive statistics of $CS_{1–5}$ and ACS were calculated for age groups, separately for male and female participants in the half-marathon. To confirm Hypothesis 2c, a mixed between-within subjects ANOVA was conducted to examine the influence of age group on change of speed in the five race segments (separately for men and women). This statistical analysis was used to assess the interaction between segment CS and age group (segment CS × age group), the main effects for a segment CS (within-subjects factor) and the main effects for an age group (between-subjects factor).

For a more detailed analysis and confirmation of Hypothesis 2c, a two-way between-groups ANOVA was conducted to examine the influence of age group and sex on ACS. The same procedure was used to investigate the interaction between sex and age group (sex × age group), the main effects of sex and the main effects of age group. In this way we analyzed ACS between male and female runners within each age group in the half-marathon.

5.5.3. Analysis of Pacing Strategies in the Marathon

Descriptive statistics of the average speed for each race segment were calculated for the overall sample (both sexes) in the marathon. To confirm Hypothesis 3, a repeated measures ANOVA was conducted to examine the difference in average speed between each of the five race segments in the overall sample from the marathon.

5.5.3.1. *Analysis of Pacing Strategies Based on Performance Level*

Descriptive statistics of $CS_{1\text{-}5}$ and ACS were calculated separately for male and female runners in four groups of participants based on their performance level in the marathon. To confirm Hypothesis 3a, a mixed between-within subjects ANOVA was conducted to examine the influence of performance level on $CS_{1–5}$ (separately for men and women). This statistical analysis was used to assess the interaction between segment CS and performance level (segment CS × performance level), the main effects for a segment CS (within-subjects factor) and the main effects for performance level (between-subjects factor).

For a more detailed analysis and confirmation of Hypothesis 3a, a two-way between-groups ANOVA was conducted to examine the influence of performance level and sex on ACS. The same procedure was used to investigate the interaction between sex and performance level (sex × performance level), the main effects of sex and the main effects of performance level. In this way we analyzed ACS between male and female runners within each performance group in the marathon.

5.5.3.2. *Analysis of Pacing Strategies Based on Sex*

Descriptive statistics of $CS_{1–5}$ and ACS were calculated separately for male and female participants in the marathon. To confirm Hypothesis 3b, a mixed between-within subjects ANOVA was conducted to examine the influence of sex on change of speed in the five race segments. This statistical analysis was used to assess the interaction between segment CS and sex (segment CS × sex), the main effects for a segment CS (within-subjects factor) and the main effects for sex (between-subjects factor).

5.5.3.3. *Analysis of Pacing Strategies Based on Age*

Descriptive statistics of $CS_{1–5}$ and ACS were calculated for age groups, separately for male and female participants in the marathon. To confirm Hypothesis 3c, a mixed between-within subjects ANOVA was conducted to examine the influence of age group on change of speed in the five race segments (separately for men and women). This statistical analysis was used to assess the interaction between segment CS and age group (segment CS × age group), the main effects for a segment CS (within-subjects factor) and the main effects for age group (between-subjects factor).

For a more detailed analysis and confirmation of Hypothesis 3c, a two-way between-groups ANOVA was conducted to examine the influence of age group and sex on ACS. The same procedure was used to investigate the interaction between sex and age group (sex × age group), the main effects of sex and the main effects for age group. In this way we analyzed ACS between male and female runners within each age group in the marathon.

6. RESULTS

6.1. Comparison of Pacing Strategies in the Half-Marathon and Marathon

To examine Hypothesis 1, the $CS_{1–5}$ and ACS for the overall sample (both sexes), separately in the half-marathon and marathon are presented in Figure 3. A mixed between-within subjects ANOVA was conducted to assess the impact of two different races on runners' average change of speed across five race segments (Figure 3). There was a significant interaction between race and segment CS, Wilks' Λ (Lambda) = 0.96, $F(4, 233042) = 2125$, $p < 0.001$, however, with a very small effect size, $\eta^2 = 0.005$. There was a substantial main effect for segment CS, Wilks' $\Lambda = 0.43$, $F(4, 233042) = 75946$, $p < 0.001$, with a large practical significance, $\eta^2 = 0.154$. Both groups of runners exhibited significant differences in CS between segments, with a decrease in speed variability up to the fourth segment, followed by an increase in the fourth segment. In the fifth segment, a significant increase in speed variability was observed in half-marathon runners, indicating a pronounced ES. In contrast, marathoners showed a decrease in speed variability in the same segment, indicating a less pronounced ES. A non-significant difference was observed between the fourth and fifth segments in the marathon. The main effect comparing the two races was significant, $F(1, 233045) = 5370$, $p < 0.001$, but again with a very small effect size, $\eta^2 = 0.008$.

An independent-sample t-test was conducted to compare the ACS for half-marathoners and marathoners. There was a significant difference in ACS for half-marathoners (mean = 4.66±2.62) and marathoners (mean = 5.54±3.84), with $t(130565) = –24.41$ and $p < 0.001$, two-tailed. The magnitude of the differences in the means (mean difference = –0.03, 95% CI: –0.03 to –0.03) was very small ($\eta^2 = 0.003$), suggesting negligible practical significance (Cohen, 1988, pp. 284–288).

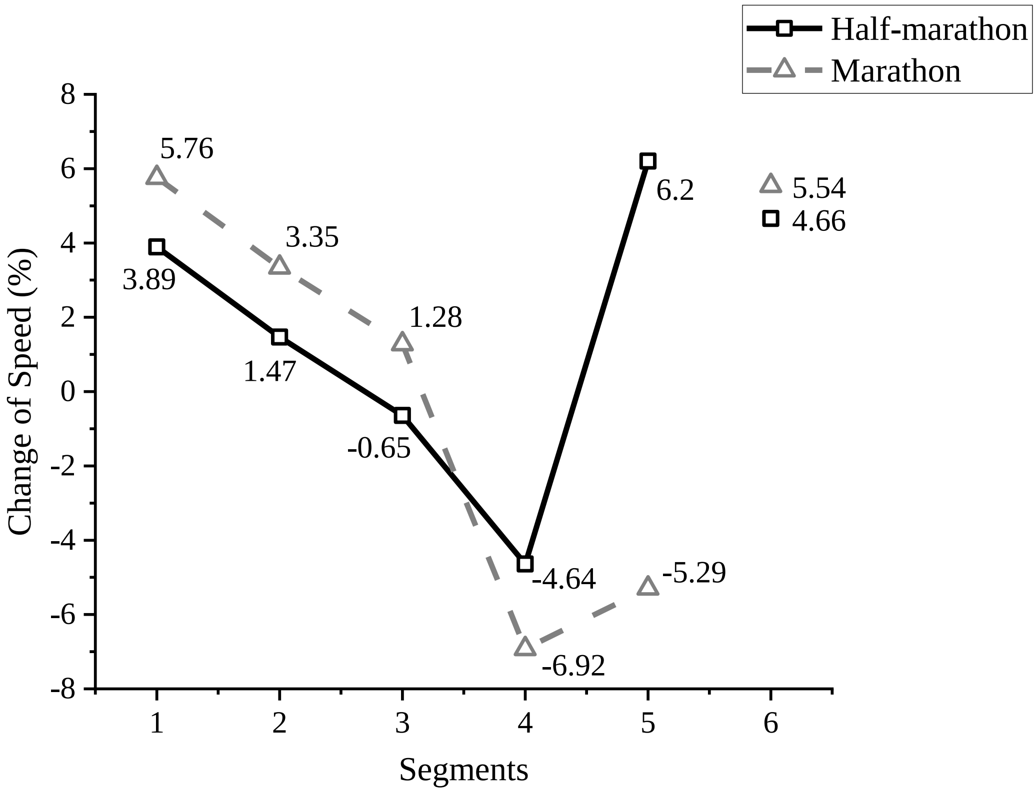


Figure 3. The average change of speed in each race segment and absolute change of speed (values shown separately on the right) in all participants in the half-marathon and marathon.

6.1.1. Comparison Based on Performance Level

Descriptive statistics of segments and average race speed for all performance levels of male and female half-marathon and marathon runners are presented in Tables 3 and 4. We have observed positive PS among all performance groups, including male and female runners, in both the half-marathon and marathon races. Furthermore, the majority of these groups exhibited an ES. Notably, faster runners displayed less of an ES compared to slower runners.

Table 3. *Segments and average race speed for all performance levels of men half-marathon and marathon runners.*

Men									
		Half-marathon (N=100,695)				**Marathon** (N=6,7118)			
	DS	**LL**	**MLL**	**MHL**	**HL**	**LL**	**MLL**	**MHL**	**HL**
Segment 1 (km/h)	Mean	9.44	10.58	11.54	13.39	9.83	10.90	11.86	13.66
	SD	0.84	0.67	0.68	1.30	0.84	0.70	0.74	1.36
	Min	4.49	6.70	7.53	8.96	6.03	7.57	8.68	9.47
	Max	13.41	14.88	16.58	21.25	13.87	15.06	15.78	20.18
Segment 2 (km/h)	Mean	9.10	10.41	11.38	13.15	9.43	10.72	11.73	13.49
	SD	0.80	0.51	0.54	1.17	0.85	0.60	0.65	1.30
	Min	5.39	7.66	7.92	9.82	5.78	7.59	8.03	9.58
	Max	12.78	14.55	14.77	20.57	13.37	14.16	15.44	20.17
Segment 3 (km/h)	Mean	8.70	10.25	11.29	13.05	8.96	10.53	11.62	13.42
	SD	0.88	0.54	0.54	1.14	0.91	0.57	0.60	1.31
	Min	4.78	6.23	6.83	8.55	4.84	7.06	7.82	9.00
	Max	12.76	14.30	14.61	20.81	13.12	13.14	15.17	20.64
Segment 4 (km/h)	Mean	8.13	9.79	10.91	12.75	7.94	9.59	10.74	12.58
	SD	0.94	0.73	0.69	1.22	0.93	0.82	0.81	1.38
	Min	4.48	5.42	6.28	6.45	4.66	6.19	6.11	7.41
	Max	12.20	13.13	13.60	20.71	11.87	13.51	14.45	20.21
Segment 5 (km/h)	Mean	9.28	10.86	11.99	13.83	8.35	9.72	10.76	12.45
	SD	1.19	1.03	1.01	1.39	1.03	1.03	1.04	1.47
	Min	4.52	5.13	5.80	6.72	4.60	4.98	4.64	5.65
	Max	14.63	16.06	17.18	21.83	13.30	14.94	15.28	21.02
Average race speed (km/h)	Mean	8.81	10.26	11.29	13.10	8.90	10.34	11.40	13.21
	SD	0.72	0.42	0.46	1.15	0.69	0.45	0.51	1.27
	Min	5.65	7.93	8.91	9.94	6.30	8.05	8.65	9.56
	Max	9.86	10.93	12.13	20.80	9.98	11.12	12.40	20.23

DS – Descriptive Statistics; Mean – Mean value; SD – Standard Deviation; Min – Minimal value; Max – Maximal value. Performance groups: LL – Low-Level; MLL – Moderate to Low-Level; MHL – Moderate to High-Level; HL – High-Level.

Table 4. *Segments and average race speed for all performance levels in women half-marathon and marathon runners.*

Women									
		Half-marathon (N=49,537)				**Marathon** (N=15,697)			
	DS	**LL**	**MLL**	**MHL**	**HL**	**LL**	**MLL**	**MHL**	**HL**
Segment 1 (km/h)	Mean	8.69	9.58	10.33	11.67	9.06	9.91	10.65	12.15
	SD	0.67	0.54	0.53	1.01	0.63	0.55	0.52	1.39
	Min	4.64	7.07	7.47	7.80	6.72	8.27	8.72	9.42
	Max	12.45	12.35	14.13	18.54	12.26	12.65	14.06	18.21
Segment 2 (km/h)	Mean	8.27	9.34	10.15	11.47	8.56	9.60	10.44	11.95
	SD	0.61	0.41	0.40	0.92	0.63	0.45	0.44	1.34
	Min	5.89	7.42	8.09	9.25	5.13	7.78	8.58	9.17
	Max	11.84	11.97	13.96	17.43	11.35	12.26	12.31	18.15
Segment 3 (km/h)	Mean	7.88	9.11	10.00	11.36	8.27	9.46	10.38	11.94
	SD	0.68	0.44	0.44	0.92	0.66	0.44	0.45	1.31
	Min	4.89	6.63	7.36	8.75	4.88	7.14	7.57	8.43
	Max	10.86	11.01	14.25	17.29	10.30	11.98	11.68	18.09
Segment 4 (km/h)	Mean	7.52	8.74	9.66	11.10	7.64	8.83	9.81	11.38
	SD	0.71	0.54	0.55	0.97	0.71	0.58	0.60	1.30
	Min	4.62	5.74	6.77	7.34	5.33	6.39	6.45	7.42
	Max	10.23	11.44	12.29	17.06	10.64	11.03	11.96	17.98
Segment 5 (km/h)	Mean	8.67	9.89	10.76	12.19	8.14	9.14	10.01	11.45
	SD	0.94	0.77	0.78	1.12	0.82	0.74	0.77	1.34
	Min	4.57	4.49	5.71	6.06	4.51	5.39	6.39	6.33
	Max	12.16	14.06	14.91	18.64	12.19	11.88	12.93	17.80
Average race speed (km/h)	Mean	8.07	9.20	10.05	11.43	8.31	9.40	10.28	11.81
	SD	0.55	0.31	0.34	0.90	0.52	0.34	0.37	1.28
	Min	5.61	7.48	8.40	9.15	6.30	7.69	7.97	8.86
	Max	8.89	9.77	10.69	17.57	9.13	10.03	11.00	17.96

DS – Descriptive Statistics; Mean – Mean value; SD – Standard Deviation; Min – Minimal value; Max – Maximal value. Performance groups: LL – Low-Level; MLL – Moderate to Low-Level; MHL – Moderate to High-Level; HL – High-Level.

To examine Hypothesis 1a, a two-way between-groups ANOVA was conducted to explore the impact of performance level and race on ACS (Figures 4 and 9). Regarding only male runners (Figure 4), the interaction effect between performance level and race was significant, $F (3, 167805) = 52.47$, $p < 0.001$. However, the effect size was very small, $\eta^2 = 0.001$. There was a significant main effect for performance level, $F (3, 167805) = 11238$, $p < 0.001$, with large practical significance, $\eta^2 = 0.16$. Post-hoc comparisons using the Bonferroni test showed that all performance groups differ significantly from each other ($p < 0.001$). Furthermore, the main effect for race was significant, $F (1, 167805) = 1989$, $p < 0.001$, with a small effect size, $\eta^2 = 0.010$. The Bonferroni test showed that within each performance group races differed significantly from each other ($p < 0.001$).

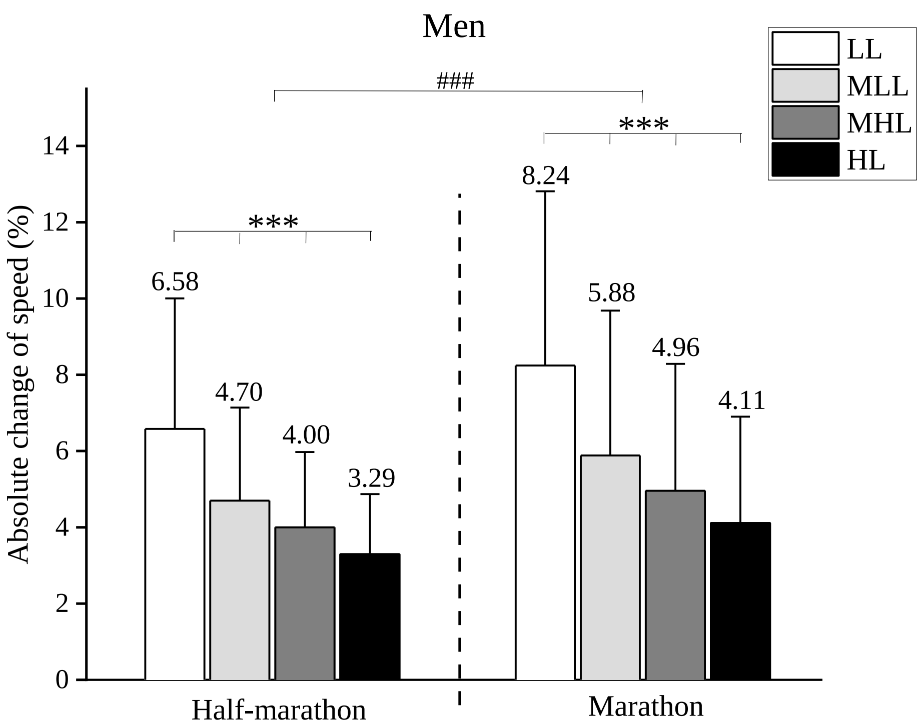


Figure 4. Absolute change of speed in men's half-marathon and marathon runners.
Performance groups: LL – Low-Level; MLL – Moderate to Low-Level; MHL – Moderate to High-Level; HL – High-Level. Error bars represent standard deviation. *** p < 0.001; ### p < 0.001.

Regarding only female runners (Figure 5), the interaction effect between performance level and race was significant, $F(3, 65226) = 35.05$, $p < 0.001$, however, the effect size was small, $\eta^2 = 0.001$ (Cohen, 1988, pp. 284–288). There was a significant main effect for performance level, $F(3, 65226) = 4240$, $p < 0.001$, $\eta^2 = 0.161$. Post-hoc comparisons using the Bonferroni test show that all performance groups differ significantly from each other ($p < 0.001$). Also, the main effect for race was significant, $F(1, 65226) = 1085$, $p < 0.001$, but with a small effect size, $\eta^2 = 0.014$. The Bonferroni test showed that within each performance group, races differed significantly from each other ($p < 0.001$).

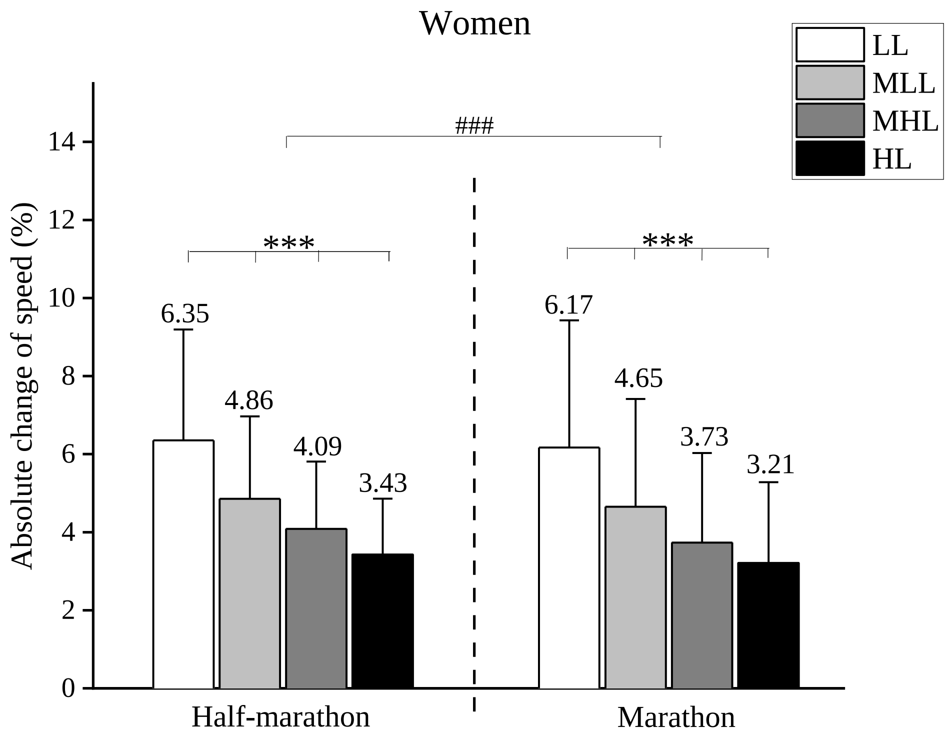


Figure 5. Absolute change of speed in women's half-marathon and marathon runners.
Performance groups: LL – Low-Level; MLL – Moderate to Low-Level; MHL – Moderate to High-Level; HL – High-Level. Error bars represent standard deviation. *** $p < 0.001$; ### $p < 0.001$.

6.1.2. Comparison Based on Sex

Descriptive statistics of segments and average race speed of male and female half-marathon and marathon runners are presented in Table 5. We observed that both sexes demonstrated faster average race speeds in the marathon compared to the half-marathon race.

Table 5. *Segments and average race speed of men and women half-marathon and marathon runners.*

		Half-marathon (N=150,232)		**Marathon** (N=82,815)	
	DS	**Men** (N=100,695)	**Women** (N=49,537)	**Men** (N=67,118)	**Women** (N=15,697)
Segment 1 (km/h)	Mean	11.23	10.07	11.56	10.44
	SD	1.71	1.31	1.70	1.42
	Min	4.49	4.64	6.03	6.72
	Max	21.25	18.54	20.18	18.21
Segment 2 (km/h)	Mean	11.01	9.81	11.34	10.13
	SD	1.68	1.32	1.73	1.48
	Min	5.39	5.89	5.78	5.13
	Max	20.57	17.43	20.17	18.15
Segment 3 (km/h)	Mean	10.82	9.59	11.13	10.01
	SD	1.78	1.43	1.86	1.56
	Min	4.78	4.89	4.84	4.88
	Max	20.81	17.29	20.64	18.09
Segment 4 (km/h)	Mean	10.39	9.25	10.21	9.41
	SD	1.91	1.49	1.97	1.61
	Min	4.48	4.62	4.66	5.33
	Max	20.71	17.06	20.21	17.98
Segment 5 (km/h)	Mean	11.49	10.38	10.32	9.68
	SD	2.03	1.57	1.89	1.54
	Min	4.52	4.49	4.60	4.51
	Max	21.83	18.64	21.02	17.80
Average race speed (km/h)	Mean	10.86	9.69	10.96	9.95
	SD	1.73	1.35	1.76	1.48
	Min	5.65	5.61	6.30	6.30
	Max	20.80	17.57	20.23	17.96

DS – Descriptive Statistics; Mean – Mean value; SD – Standard Deviation; Min – Minimal value; Max – Maximal value.

Following Hypothesis 1b, a two-way between-groups ANOVA was conducted to explore the impact of sex and race on ACS (Figure 6). The interaction effect between sex and race was significant, F (1, 233043) = 1847, $p < 0.001$. However, the effect size was very small, $\eta^2 = 0.008$. There was a significant main effect for sex, F (1, 233043) = 854. 7, $p < 0.001$, but with a very small effect size, $\eta^2 = 0.004$. The main effect for race was also significant, F (1, 233043) = 5.87, $p < 0.05$, but with a trivial effect size as well, $\eta^2 = 0.000$, suggesting negligible practical significance (Cohen, 1988, pp. 284–288).

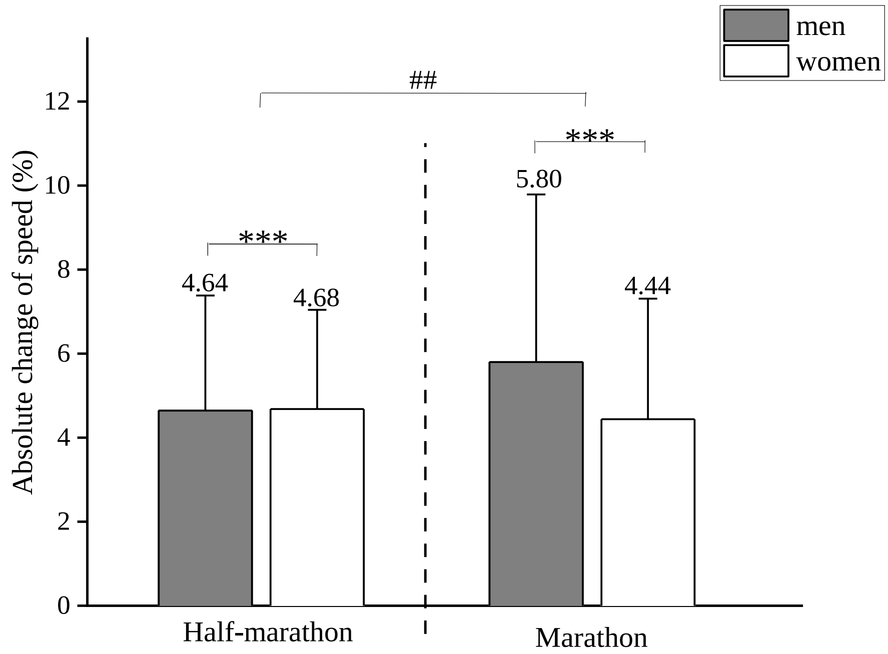


Figure 6. Absolute change of speed in men’s and women’s half-marathon and marathon runners.
Error bars represent standard deviation. *** $p < 0.001$; ## $p < 0.05$.

6.1.3. Comparison Based on Age

Descriptive statistics of segments and average race speed for all age groups of male and female half-marathon and marathon runners are presented in Tables 6–9. All age groups demonstrated higher average race speeds in the marathon compared to the half-marathon, except for the two oldest groups of male runners and the oldest group of female runners.

Table 6. *Segments and average race speed for all age groups of men half-marathon runners.*

Men							
Half-marathon (N=100,695)							
	DS	**18–29** (N=19,366)	**30–39** (N=29,519)	**40–49** (N=29,518)	**50–59** (N=17,377)	**60–69** (N=4,315)	**≥70** (N=600)
Segment 1 (km/h)	Mean	11.36	11.40	11.31	10.95	10.42	9.54
	SD	1.81	1.76	1.65	1.54	1.40	1.26
	Min	4.84	4.69	5.17	5.71	4.49	5.58
	Max	21.25	21.13	21.25	18.50	16.41	13.32
Segment 2 (km/h)	Mean	11.21	11.21	11.05	10.67	10.09	9.15
	SD	1.75	1.71	1.61	1.53	1.44	1.36
	Min	6.18	5.93	5.47	6.10	5.94	5.39
	Max	20.57	20.36	20.57	17.36	15.86	13.27
Segment 3 (km/h)	Mean	11.06	11.03	10.87	10.45	9.84	8.89
	SD	1.86	1.80	1.70	1.64	1.55	1.50
	Min	5.35	4.95	5.05	4.89	4.78	5.40
	Max	20.07	20.81	20.64	17.09	15.69	15.25
Segment 4 (km/h)	Mean	10.63	10.62	10.43	10.00	9.40	8.47
	SD	2.02	1.94	1.84	1.76	1.64	1.56
	Min	4.48	4.84	4.51	4.81	4.63	4.79
	Max	19.98	20.71	20.36	17.21	15.29	13.44
Segment 5 (km/h)	Mean	11.92	11.75	11.46	10.99	10.33	9.29
	SD	2.13	2.05	1.94	1.84	1.72	1.68
	Min	4.70	4.61	4.52	4.70	4.70	5.38
	Max	20.37	21.83	20.37	17.88	16.13	14.06
Average race speed (km/h)	Mean	11.07	11.06	10.91	10.51	9.92	8.99
	SD	1.81	1.77	1.67	1.59	1.48	1.40
	Min	5.90	6.07	6.05	5.98	6.04	5.65
	Max	20.41	20.80	20.67	17.44	15.80	13.41

DS – Descriptive Statistics; Mean – Mean value; SD – Standard Deviation; Min – Minimal value; Max – Maximal value.

Table 7. *Segments and average race speed for all age groups of men marathon runners.*

Men							
Marathon (N=67,118)							
	DS	**18–29** (N=8,347)	**30–39** (N=18,219)	**40–49** (N=23,826)	**50–59** (N=13,471)	**60–69** (N=2,964)	**≥70** (N=291)
Segment 1 (km/h)	Mean	11.55	11.85	11.67	11.23	10.58	9.67
	SD	1.96	1.84	1.59	1.43	1.29	0.99
	Min	7.13	6.69	6.03	6.73	6.89	6.88
	Max	20.17	20.18	19.51	17.18	16.38	12.56
Segment 2 (km/h)	Mean	11.40	11.68	11.46	10.94	10.22	9.19
	SD	1.99	1.85	1.60	1.48	1.36	1.10
	Min	5.78	6.17	5.87	5.97	6.43	6.58
	Max	20.17	20.17	18.43	16.96	14.99	12.57
Segment 3 (km/h)	Mean	11.17	11.49	11.26	10.71	9.94	8.84
	SD	2.15	1.97	1.72	1.59	1.51	1.19
	Min	4.84	4.87	5.23	5.42	5.19	6.04
	Max	20.64	20.56	18.40	17.08	15.01	12.62
Segment 4 (km/h)	Mean	10.18	10.54	10.36	9.82	9.11	8.02
	SD	2.27	2.10	1.84	1.71	1.60	1.19
	Min	4.99	4.66	4.71	4.94	5.11	5.74
	Max	20.06	20.21	17.13	15.69	14.44	12.21
Segment 5 (km/h)	Mean	10.47	10.65	10.41	9.90	9.21	8.11
	SD	2.08	2.00	1.80	1.66	1.54	1.22
	Min	4.61	4.69	4.60	4.70	4.62	4.64
	Max	20.69	21.02	17.37	16.16	14.58	11.83
Average race speed (km/h)	Mean	10.97	11.29	11.09	10.58	9.86	8.82
	SD	2.02	1.88	1.64	1.50	1.40	1.06
	Min	6.66	6.67	6.55	6.30	6.52	6.57
	Max	20.14	20.23	17.92	16.64	14.77	12.45

DS – Descriptive Statistics; Mean – Mean value; SD – Standard Deviation; Min – Minimal value; Max – Maximal value.

Table 8. *Segments and average race speed for all age groups of women half-marathon runners.*

Women							
Half-marathon (N=49,537)							
	DS	**18–29** (N=13,159)	**30–39** (N=14,985)	**40–49** (N=13,329)	**50–59** (N=6,737)	**60–69** (N=1,230)	**≥70** (N=97)
Segment 1 (km/h)	Mean	10.09	10.19	10.09	9.84	9.41	8.89
	SD	1.34	1.35	1.26	1.19	1.13	1.08
	Min	4.64	4.64	4.95	4.70	6.10	6.70
	Max	18.54	18.52	16.82	15.36	13.76	11.16
Segment 2 (km/h)	Mean	9.87	9.95	9.81	9.51	9.03	8.54
	SD	1.35	1.36	1.28	1.22	1.18	1.12
	Min	5.93	5.89	5.94	6.01	6.11	6.23
	Max	17.43	17.32	16.42	14.62	12.97	11.02
Segment 3 (km/h)	Mean	9.66	9.75	9.60	9.26	8.74	8.19
	SD	1.45	1.46	1.37	1.33	1.29	1.25
	Min	4.91	5.12	4.89	5.27	5.38	5.81
	Max	17.03	17.29	16.50	14.42	13.14	11.04
Segment 4 (km/h)	Mean	9.35	9.43	9.25	8.87	8.36	7.84
	SD	1.53	1.53	1.42	1.37	1.30	1.23
	Min	4.62	4.67	4.64	5.04	5.23	5.20
	Max	16.76	17.06	16.01	14.23	13.00	11.09
Segment 5 (km/h)	Mean	10.58	10.58	10.31	9.88	9.31	8.66
	SD	1.61	1.60	1.49	1.43	1.34	1.29
	Min	4.65	4.57	4.81	4.49	6.02	5.98
	Max	18.55	18.64	17.64	15.31	13.67	12.01
Average race speed (km/h)	Mean	9.75	9.84	9.69	9.37	8.87	8.35
	SD	1.37	1.39	1.30	1.25	1.19	1.15
	Min	5.76	5.92	5.61	6.04	6.06	6.06
	Max	17.22	17.57	16.43	14.48	13.10	10.93

DS – Descriptive Statistics; Mean – Mean value; SD – Standard Deviation; Min – Minimal value; Max – Maximal value.

Table 9. *Segments and average race speed for all age groups of women marathon runners.*

Women							
Marathon (N=15,697)							
	DS	**18–29** (N=2,392)	**30–39** (N=4,604)	**40–49** (N=5,537)	**50–59** (N=2,764)	**60–69** (N=381)	**≥70** (N=18)
Segment 1 (km/h)	Mean	10.60	10.65	10.42	10.11	9.65	9.14
	SD	1.78	1.55	1.24	1.08	1.01	0.89
	Min	7.03	6.73	6.72	7.12	6.89	7.66
	Max	18.07	18.03	18.21	14.30	13.42	10.96
Segment 2 (km/h)	Mean	10.34	10.39	10.11	9.72	9.19	8.49
	SD	1.81	1.59	1.30	1.18	1.12	0.91
	Min	5.13	6.02	5.87	6.36	6.78	7.28
	Max	17.79	17.94	18.15	14.25	13.11	10.36
Segment 3 (km/h)	Mean	10.21	10.28	9.99	9.56	8.99	8.17
	SD	1.88	1.67	1.37	1.27	1.21	0.99
	Min	6.04	4.88	5.70	5.92	6.34	6.59
	Max	18.07	18.09	17.96	14.26	13.04	10.15
Segment 4 (km/h)	Mean	9.58	9.68	9.42	8.96	8.36	7.37
	SD	1.92	1.72	1.44	1.32	1.19	0.84
	Min	5.39	5.33	5.58	5.43	6.03	6.39
	Max	17.94	17.98	17.16	13.77	12.91	9.32
Segment 5 (km/h)	Mean	9.94	9.97	9.66	9.19	8.56	7.67
	SD	1.77	1.64	1.39	1.27	1.16	0.66
	Min	5.82	4.51	4.57	5.12	4.60	6.53
	Max	17.80	17.80	16.67	14.47	13.28	9.22
Average race speed (km/h)	Mean	10.13	10.20	9.94	9.53	8.98	8.20
	SD	1.80	1.59	1.30	1.18	1.09	0.82
	Min	6.69	6.63	6.30	6.65	6.77	7.16
	Max	17.96	17.95	17.80	14.07	13.12	9.98

DS – Descriptive Statistics; Mean – Mean value; SD – Standard Deviation; Min – Minimal value; Max – Maximal value.

To examine Hypothesis 1c, a two-way between-groups ANOVA was conducted separately for male and female runners to explore the impact of age groups and race on ACS (Figures 7 and 8). Regarding only male runners (Figure 7), the interaction effect between age groups and race was significant, F (5, 167801) = 36.91, $p < 0.001$, however, the effect size was very small, $\eta^2 = 0.001$. There was a significant main effect for age groups, F (5, 167801) = 241.7, $p < 0.001$, but the effect size was also very small, $\eta^2 = 0.007$. Also, the main effect for race was significant, F (1, 167801) = 537, $p < 0.001$, with a very small effect size here as well, $\eta^2 = 0.003$, suggesting negligible practical significance (Cohen, 1988, pp. 284–288). Post-hoc comparisons using the Bonferroni test show that half-marathoners and marathoners differ from each other significantly in each age group ($p < 0.001$).

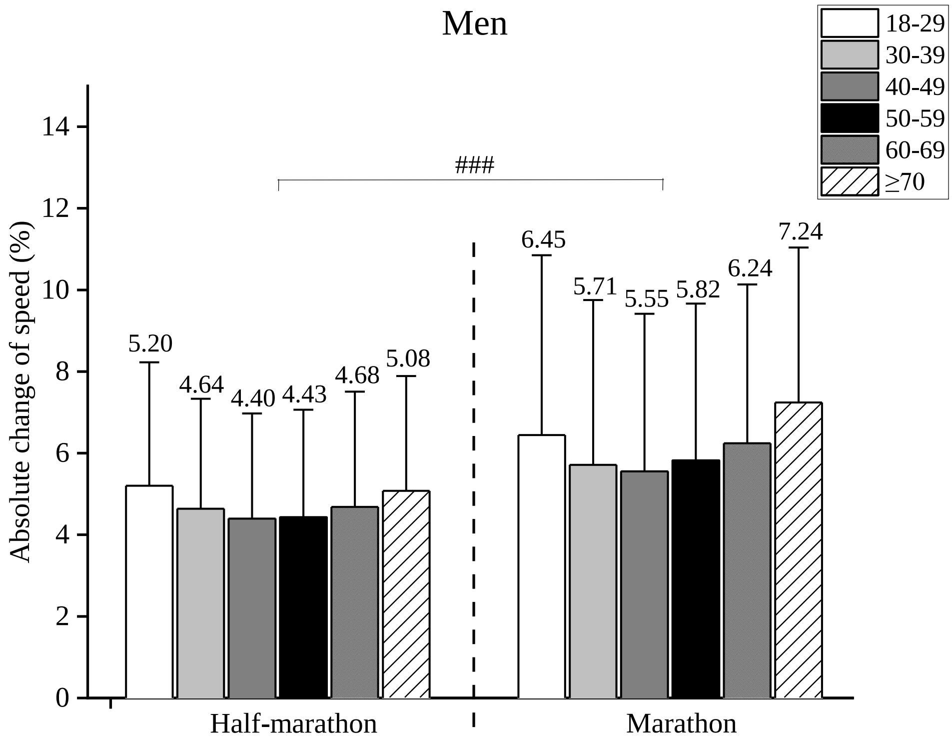


Figure 7. Absolute change of speed in age groups of men's half-marathon and marathon runners. Error bars represent standard deviation. ### $p < 0.001$.

Regarding only female runners (Figure 8), the interaction effect between age groups and race was significant, F (5, 65222) = 23.07, $p < 0.001$. However, the effect size was very small, $\eta^2 = 0.002$. There was a significant main effect for age groups, F (5, 65222) = 81.77, $p < 0.001$, but the effect size was also very small, $\eta^2 = 0.006$. The main effect for race was not significant, F (1, 65222) = 1.44, $p = 0.230$. Post-hoc comparisons using the Bonferroni test revealed significant differences in mostly age groups between half-marathoners and marathoners, with a significance level of $p < 0.001$. Only in the ≥70 age group, the significance level was $p < 0.05$, and in the 60–69 age group, there was no significant difference ($p = 0.150$). However, a lower level of significance in the oldest age group, as well as an absence of significance in the 60–69 age group might be attributed to the lowest number of participants, especially in the marathon (N = 381 and N = 18, respectively). Post-hoc comparisons of ACS were conducted using the Bonferroni test, whereby each age group was compared to all other age groups in male and female runners separately, for both the half-marathon and marathon. The results are presented in Tables 12 and 15.

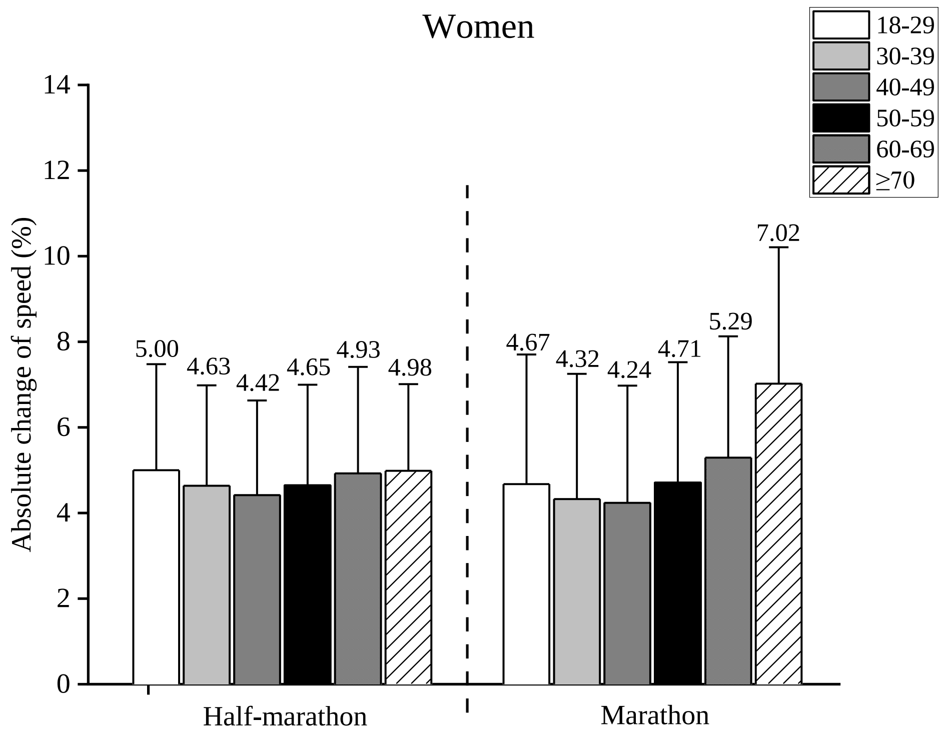


Figure 8. Absolute change of speed in age groups of women's half-marathon and marathon runners. Error bars represent standard deviation.

6.2. Analysis of Pacing Strategies in the Half-Marathon

Descriptive statistics of segments and average race speed of male and female half-marathon runners are presented in Table 5. Following Hypothesis 2, the pace profile of all participants in the half-marathon is presented in Figure 9. Additionally, repeated analyses of variance were conducted to explore the differences between each segment's mean speed. There was a significant difference, Wilks' $\Lambda = 0.24$, $F(4, 150228) = 121000$, $p < 0.001$, with large effect size, $\eta^2 = 0.350$. All half-marathoners exhibited a decrease in speed up to the fifth segment, followed by an increase in the fifth segment, indicating a noticeable ES. Post-hoc comparisons using the Bonferroni test revealed significant differences between all segments, with a significance level of $p < 0.001$.

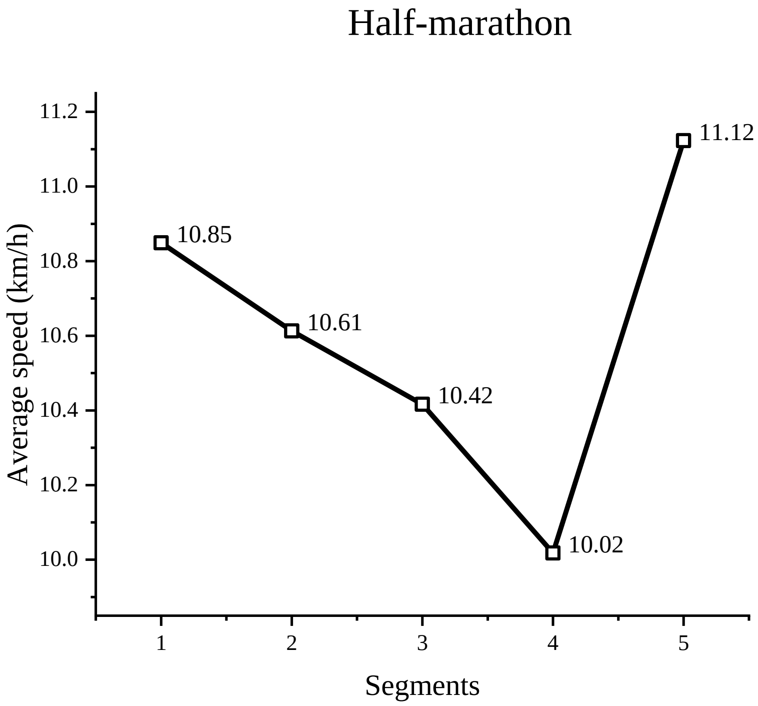


Figure 9. The average speed in each race segment of all participants in the half-marathon.

6.2.1. Analysis of Pacing Strategies Based on Performance Level

Descriptive statistics of segments and average race speed for all performance levels in male and female half-marathon runners are presented in Tables 3 and 6. To examine Hypothesis 2a, a mixed between-within subjects ANOVA was conducted to assess the impact of performance level on participants' average change of speed across five race segments (Figures 10 and 15). Regarding only male half-marathon runners (Figure 10), there was significant interaction between performance level and segment CS, Wilks' $\Lambda = 0.95$, $F(12, 266395) = 447.9$, $p < 0.001$. However with a very small effect size, almost reaching the threshold for a small effect, $\eta^2 = 0.010$. There was a substantial main effect for segment CS, Wilks' $\Lambda = 0.39$, $F(4, 100688) = 38713$, $p < 0.001$, with a large effect size as well, $\eta^2 = 0.191$. All performance groups of runners show a decrease in speed variability up to the fourth segment, and then an increase in the fourth and fifth segments. The main effect comparing performance groups was significant, $F(3, 100691) = 7449$, $p < 0.001$, but with a small effect size, almost reaching the threshold for a medium effect, $\eta^2 = 0.052$. Post-hoc comparisons using the Bonferroni test revealed significant differences in all performance groups between each segment CS, with a significance level of $p < 0.001$.

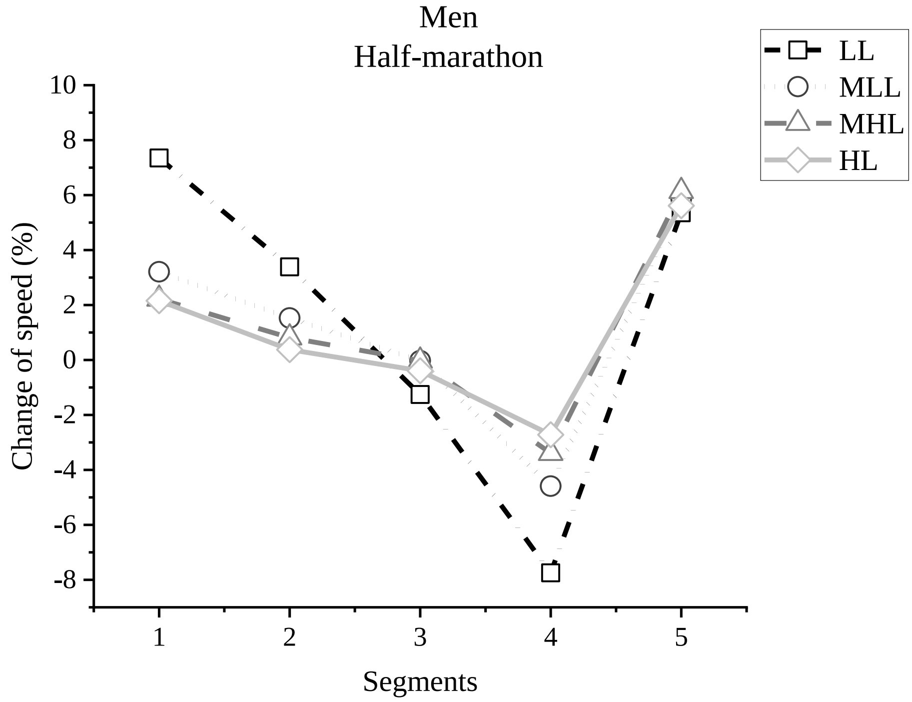


Figure 10. The average change of speed in each race segment in men in the half-marathon.
Performance groups: LL – Low-Level; MLL – Moderate to Low-Level; MHL – Moderate to High-Level; HL – High-Level.

Regarding only female half-marathon runners (Figure 11), there was a significant interaction between performance level and segment CS, Wilks' $\Lambda = 0.95$, $F(12, 131044) = 220.9$, $p < 0.001$. However, with a very small effect size, almost reaching the threshold for a small effect, $\eta^2 = 0.009$. A substantial main effect for segment CS was observed, Wilks' $\Lambda = 0.36$, $F(4, 49530) = 22137$, $p < 0.001$, with a large effect size, $\eta^2 = 0.23$. The speed variability of all performance groups of runners decreases until the fourth segment, after which it increases in both the fourth and fifth segments. The main effect comparing performance groups was significant, $F(3, 49533) = 3739$, $p < 0.001$, but with a small effect size, $\eta^2 = 0.047$. Post-hoc comparisons using the Bonferroni test revealed significant differences in almost all performance groups between each segment CS, with a significance level of $p < 0.001$. The differences were not found only in the HL group between the second and third segments ($p = 1$) and in the LL group between the first and fourth segments ($p = 0.753$). However, the lack of significant differences in the LL group between these segments can be attributed to the use of only positive values for statistical analysis, while the figures presented both positive and negative values.

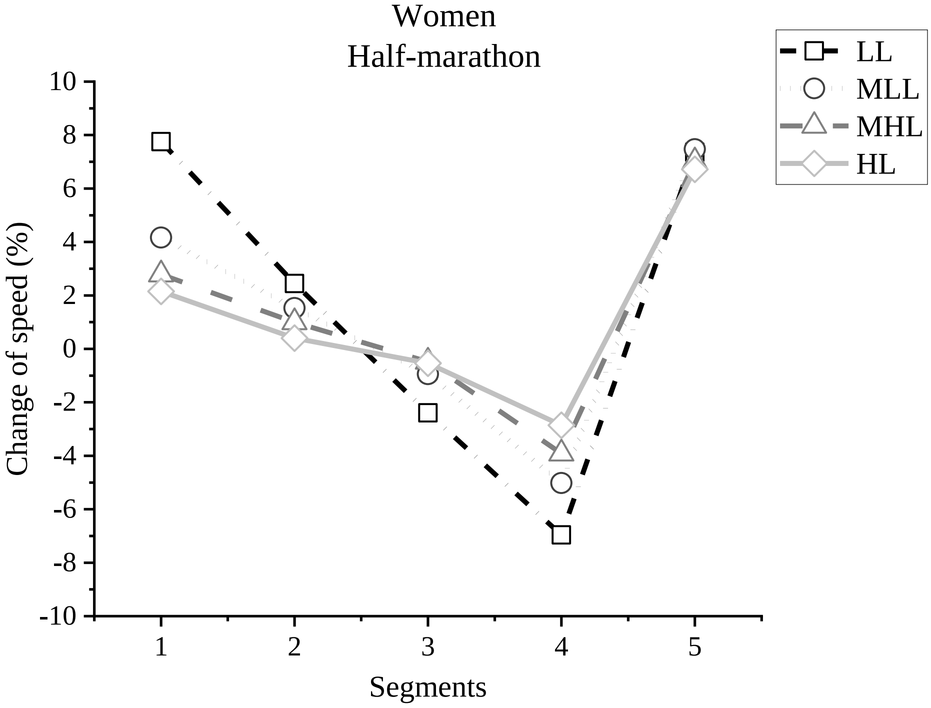


Figure 11. The average change of speed in each race segment in men in the half-marathon. Performance groups: LL – Low-Level; MLL – Moderate to Low-Level; MHL – Moderate to High-Level; HL – High-Level.

According to the second part of Hypothesis 2a, a two-way between-groups ANOVA was conducted to explore the impact of performance level and sex on ACS in the half-marathon (Figure 12). The interaction effect between performance level and sex was significant, F (3, 150224) = 34.88, $p < 0.001$. However, the effect size was very small, $\eta^2 = 0.001$. There was a significant main effect for performance level, F (3, 150224) = 11171, $p < 0.001$, $\eta^2 = 0.182$. Post-hoc comparisons using the Bonferroni test show that all performance groups inside of each sex differ significantly from each other ($p < 0.001$). The main effect for sex was significant, F (1, 150224) = 285.4, $p < 0.001$, but also with a very small effect size, $\eta^2 = 0.002$. Also, post-hoc comparisons using the Bonferroni test showed that in each performance group male and female participants differ significantly from each other at a significance level of $p < 0.001$, except in the LL group, where significance does not exist ($p = 0.820$).

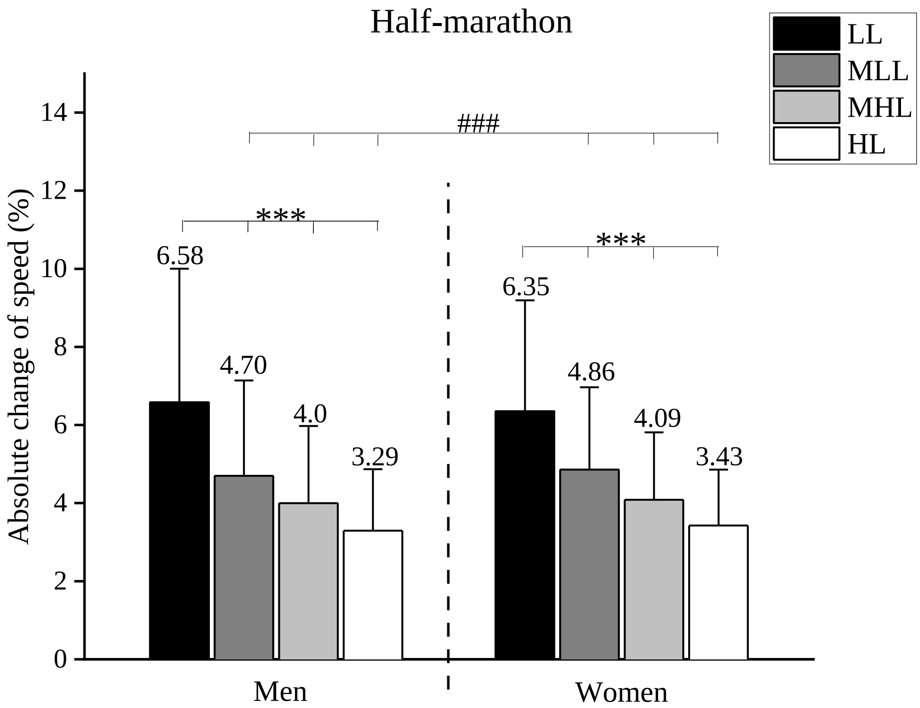


Figure 12. Absolute change of speed in men's and women's half-marathon runners.
Performance groups: LL – Low-Level; MLL – Moderate to Low-Level; MHL – Moderate to High-Level; HL – High-Level. Error bars represent standard deviation. *** $p < 0.001$; ### $p < 0.001$.

6.2.2. Analysis of Pacing Strategies Based on Sex

Descriptive statistics of segments and average race speed in male and female half-marathon runners are presented in Table 5. To examine Hypothesis 2b, a mixed between-within subjects ANOVA was conducted to assess the impact of sex on participants' average change of speed across five race segments in a half-marathon (Figure 13). There was a significant interaction between sex and segment CS, Wilks' $\Lambda = 1$, $F (4, 150227) = 152.8$, $p < 0.001$. However, the effect size was very small, $\eta^2 = 0.001$. There was a substantial main effect for segment CS, Wilks' $\Lambda = 0.41$, $F (4, 150227) = 53879$, $p < 0.001$, $\eta^2 = 0.187$, where both sexes of runners show a decrease in speed variability up to the fourth segment, followed by an increase in the fourth and fifth segments. The main effect comparing sexes was significant, $F (1, 150230) = 157.2$, $p < 0.001$, but the effect size was negligible, $\eta^2 = 0.000$. Additionally, post-hoc comparisons using the Bonferroni test revealed significant differences between sexes inside each segment, with a significance level of $p < 0.001$.

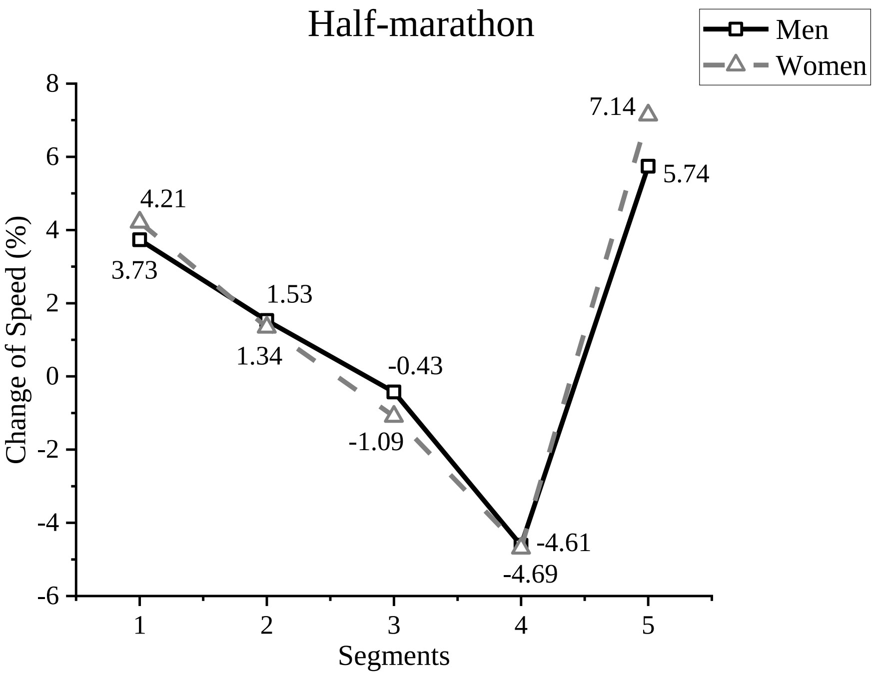


Figure 13. The average change of speed for each race segment in men's and women's half-marathon runners.

6.2.3. Analysis of Pacing Strategies Based on Age

Descriptive statistics of segments and average race speed for all age groups of male and female half-marathon runners are presented in Tables 6 and 8. To examine Hypothesis 2c, a mixed between-within subjects ANOVA was conducted to assess the impact of age group on participants' average change of speed across five race segments (Figures 14 and 15). Regarding only male half-marathon runners (Figure 14), there was a significant interaction between age group and segment CS, Wilks' $\Lambda = 0.98$, $F (20, 333938) = 76.5$, $p < 0.001$. However, the effect size was very small, $\eta^2 = 0.003$. There was a substantial main effect for segment CS, Wilks' $\Lambda = 0.8$, $F (4, 100686) = 6426$, $p < 0.001$, but with a small effect size, $\eta^2 = 0.037$. All age groups of runners show a decrease in speed variability up to the fourth segment, followed by an increase in the fourth and fifth segments. Post-hoc comparisons using the Bonferroni test show significant differences in almost all age groups between each segment CS, with a significance level of $p < 0.001$. Only a non-significant difference was found in the group 60–69, between the fourth and fifth segments and some segments in the ≥70 age group (Table 10). The lack of significance between segments in only the two oldest groups may be attributed to the smaller number of participants in these age groups. Furthermore, since all age groups demonstrated an ES, transitioning from negative values in the fourth segment to similar positive values (above the average race speed) in the fifth segment, the lack of significance can be attributed to the values used for statistical analysis. Specifically, the analysis considered only absolute values, while the figures presented the actual values, including both positive and negative ones. This same situation also contributed to the lack of significance between the first and fourth segments. The main effect comparing age groups was significant, $F (5, 100689) = 132.2$, $p < 0.001$, but with a very small effect size, $\eta^2 = 0.002$. Post-hoc comparisons using the Bonferroni test revealed significant differences between most age groups inside each segment (table 11), with a significance level of $p < 0.001$ and some of them with a significance level of $p < 0.05$.

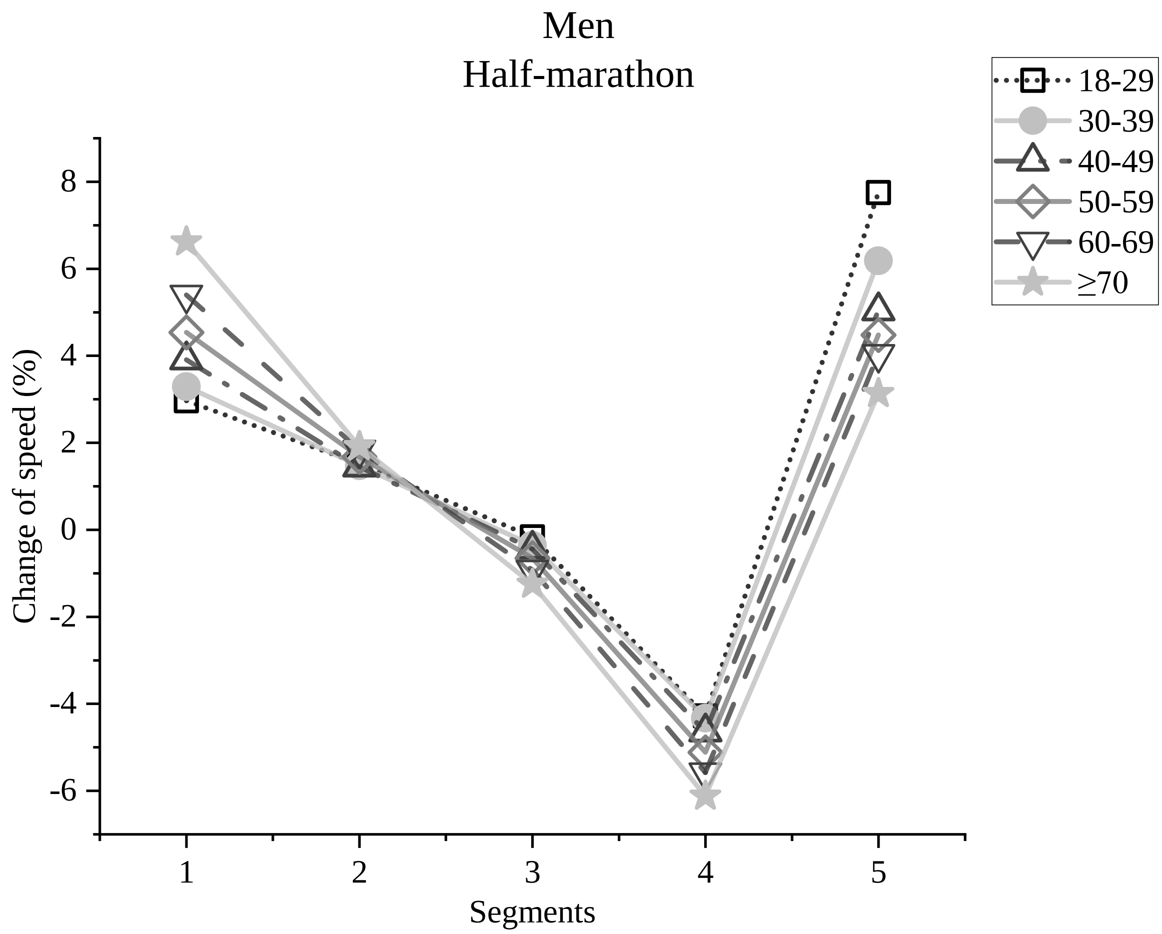


Figure 14. The average change of speed for each race segment in age groups of men's half-marathon runners.

Regarding male runners (Figure 14), the 18–29 age group demonstrated the lowest CS of 2.96% in the first segment, while it increased as the group got older, reaching 6.62% in the ≥70 age group. Slightly different results were observed in the second segment, where the 40–49 age group had the lowest CS, while the oldest group had the highest (from CS 1.45% to CS 1.92%). In the third segment, all age groups showed a decrease in speed slightly below the average race speed. The youngest group demonstrated a lowest CS of –0.16%, which increased as the age group got older, reaching –1.25% in the oldest group. The same pattern was observed in the fourth segment as well (from CS –4.28% to CS –6.12%). However, opposite was observed in the fifth segment, where the youngest age group had the most pronounced ES, which decreased as the age group got older (from CS 7.75% to CS 3.13%).

Regarding only female half-marathon runners (Figure 15), there was a significant interaction between age group and segment CS, Wilks' $\Lambda = 0.98$, $F(20, 164266) = 59.86$, $p < 0.001$, however with very small effect size, $\eta^2 = 0.005$. There was a substantial main effect for segment CS, Wilks' $\Lambda = 0.91$, $F(4, 49528) = 1209$, $p < 0.001$, also with small effect size, $\eta^2 = 0.016$. All age groups of runners show a decrease in speed variability up to the fourth segment, followed by an increase in the fourth and fifth segments. Post-hoc comparisons using the Bonferroni test show significant differences in all age groups between each segment CS up to the group 60–69, with a significance level of $p < 0.001$. The difference was not significant between some segments in the 60–69 age group and in the group aged ≥70 (Table 10). The limited significance observed between segments just within the two eldest groups could be linked to the reduced number of participants. Additionally, as previously mentioned, since the statistical analysis only considered absolute values, it was expected that the lack of significance observed between the fourth and fifth segments and between the first and fourth segments would also be present in female participants. The main effect comparing age groups was significant, F (5, 49531) = 54.11, $p < 0.001$, but with a very small effect size, $\eta^2 = 0.002$. Post-hoc comparisons using the Bonferroni test revealed significant differences between most age groups inside each segment with a significance level of $p < 0.001$ and some of them with a significance level of $p < 0.01$ and $p < 0.05$ (Table 11).

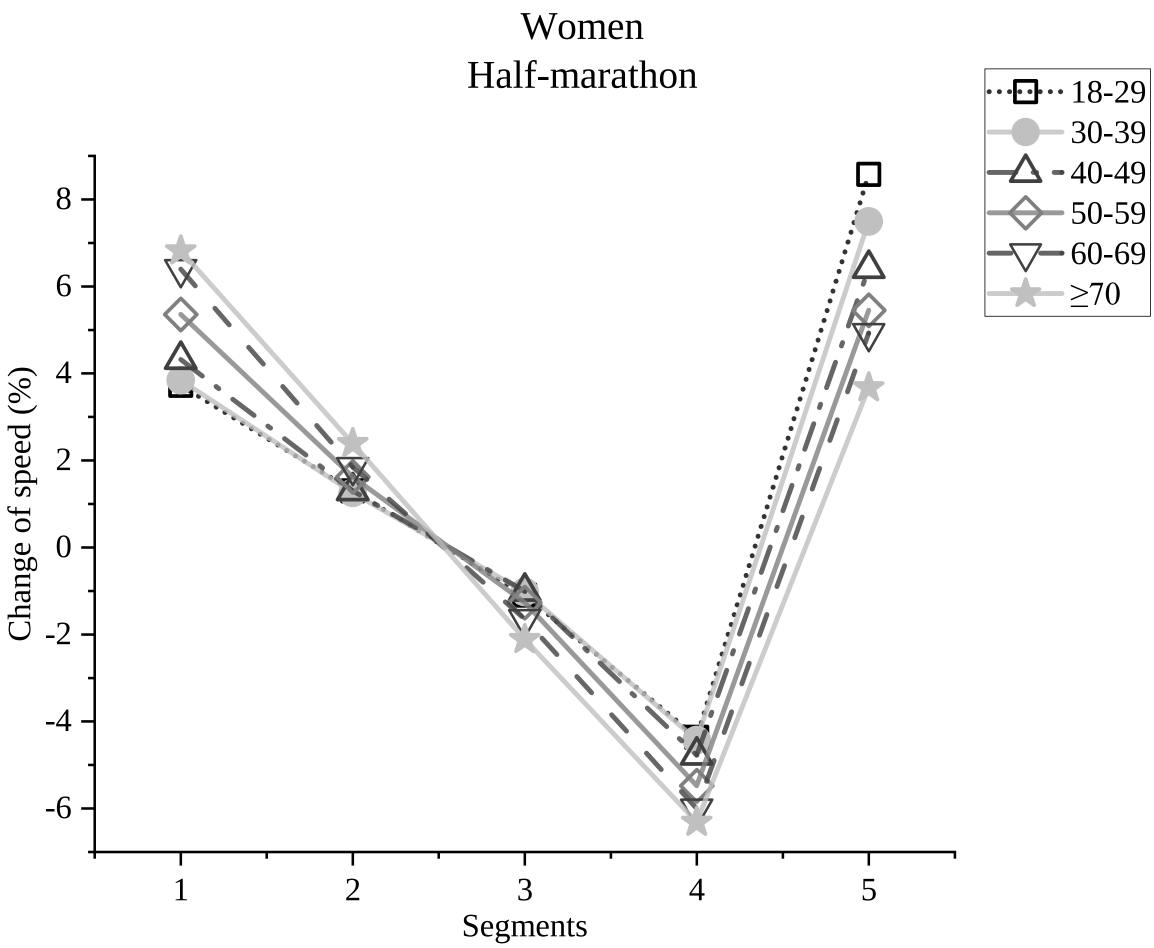


Figure 15. The average change of speed for each race segment in age groups of women's half-marathon runners.

When it comes to female participants (Figure 15), the 18–29 age group demonstrated the lowest CS (3.73%) in the first segment, while it increased as the group was older, with the highest CS in the ≥70 age group (6.82%). In the second segment, slightly different results were observed. The lowest CS (1.25%) was found in the 30–39 age group, followed by the 18–29, 40–49, 50–59, and 60–69 age groups, while the highest CS was observed in the ≥70 age group (1.297%, 1.30%, 1.62%, 1.84% and 2.39%). In the third segment, all age groups showed a decrease in speed slightly below the average race speed. The lowest CS (–1.01%) was found in the 40–49 age group, followed by the 30–39, 18–29, 50–59 and 60–69 age groups, while the highest CS was in the ≥70 age group (–1.02%, –1.1%, –1.27%, –1.65% and –2.12%). The youngest group demonstrated a lower CS of –4.37% in the fourth segment, which increased as the age group got older, reaching –6.32% in the oldest one. However, an opposite situation was observed in the fifth segment, where the youngest age group had the most pronounced ES, which decreased as the age group got older (from CS 8.57% to CS 3.67%).

Table 10. *Pairwise comparisons of average change of speed in each segment ($CS_{1–5}$) among the oldest age groups in the half-marathon, separately for men and women.*

Half-marathon				
Age group	**Segment**		**Men**	**Women**
			p	
60–69	1	2	**<0.001**	**<0.001**
		3	**<0.001**	**<0.001**
		4	**<0.001**	**0.002**
		5	**<0.001**	1.000
	2	3	**<0.001**	1.000
		4	**<0.001**	**<0.001**
		5	**<0.001**	**<0.001**
	3	4	**<0.001**	**<0.001**
		5	**<0.001**	**<0.001**
	4	5	0.385	0.191
≥70	1	2	**<0.001**	**<0.001**
		3	**<0.001**	**<0.001**
		4	0.494	1.000
		5	1.000	1.000
	2	3	1.000	1.000
		4	**<0.001**	**<0.001**
		5	**<0.001**	**<0.001**
	3	4	**<0.001**	**<0.001**
		5	**<0.001**	**<0.001**
	4	5	1.000	1.000

Bold values are statistically significant at a level of <0.05.

Table 11. *Pairwise comparisons of average change of speed in each segment ($CS_{1–5}$) between age groups in the half-marathon, separately for men and women.*

Half-marathon		**Segment 1**		**Segment 2**		**Segment 3**		**Segment 4**		**Segment 5**	
		Men	Women	Men	Women	Men	Women	Men	Women	Men	Women
Age group		p									
18–29	30–39	**<0.001**	**0.003**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	1.000	**<0.001**	**<0.001**
	40–49	**0.012**	1.000	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.504	**<0.001**	**<0.001**	**<0.001**
	50–59	0.107	**<0.001**	**<0.001**	**0.029**	**<0.001**	0.136	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	60–69	**<0.001**	**<0.001**	**<0.001**	1.000	**0.032**	**0.014**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	≥70	**<0.001**	**<0.001**	1.000	0.085	0.870	0.206	**<0.001**	**0.001**	**<0.001**	**<0.001**
30–39	40–49	**<0.001**	**0.022**	**<0.001**	**0.001**	**<0.001**	**0.003**	**0.017**	**<0.001**	**<0.001**	**<0.001**
	50–59	**<0.001**	**<0.001**	**<0.001**	0.134	**<0.001**	0.123	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	60–69	**<0.001**	**<0.001**	1.000	**0.001**	**0.037**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	≥70	**<0.001**	**<0.001**	1.000	**0.005**	**<0.001**	**0.019**	**<0.001**	**0.001**	**<0.001**	**<0.001**
40–49	50–59	**<0.001**	**<0.001**	1.000	**<0.001**	0.193	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	60–69	**<0.001**	**<0.001**	**0.016**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	≥70	**<0.001**	**<0.001**	0.244	**0.001**	**<0.001**	**0.004**	**<0.001**	**0.011**	0.221	0.130
50–59	60–69	**<0.001**	**0.001**	0.092	0.099	**<0.001**	**<0.001**	**<0.001**	**0.002**	1.000	**0.005**
	≥70	**<0.001**	**0.028**	0.390	**0.020**	**<0.001**	0.068	**<0.001**	1.000	1.000	1.000
60–69	≥70	**0.016**	0.969	1.000	0.309	**0.042**	1.000	0.122	1.000	1.000	1.000

Bold values are statistically significant at a level of <0.05.

According to the second part of Hypothesis 2c, a two-way between-groups ANOVA was conducted to explore the impact of sex and age group on ACS in half-marathon runners (Figure 16). The interaction effect between sex and age group was significant, $F(5, 150220) = 18.38$, $p < 0.001$. The effect size was, however, very small, $\eta^2 = 0.001$. There was a significant main effect for sex, $F(1, 150220) = 21.09$, $p < 0.001$, but with negligible effect size, $\eta^2 = 0.000$. Post-hoc comparisons using the Bonferroni test revealed significant differences between sexes in all age groups, with a significance level of $p < 0.001$, except in the 18–29 and ≥70 age groups where no significance was shown ($p = 0.580$ and $p = 0.434$, respectfully). Additionally, the main effect for age group was significant, $F(5, 150220) = 274.4$, $p < 0.001$, but with a very small effect size, almost reaching the threshold for a small effect, $\eta^2 = 0.009$. Post-hoc comparisons using the Bonferroni test revealed significant differences between most age groups inside of male participants, with a significance level of $p < 0.001$, some of them with a significance level of $p < 0.01$ (Table 12). Less significant differences were observed among female age groups compared to male age groups, and no significant differences were found in the oldest group compared to the others (Table 12).

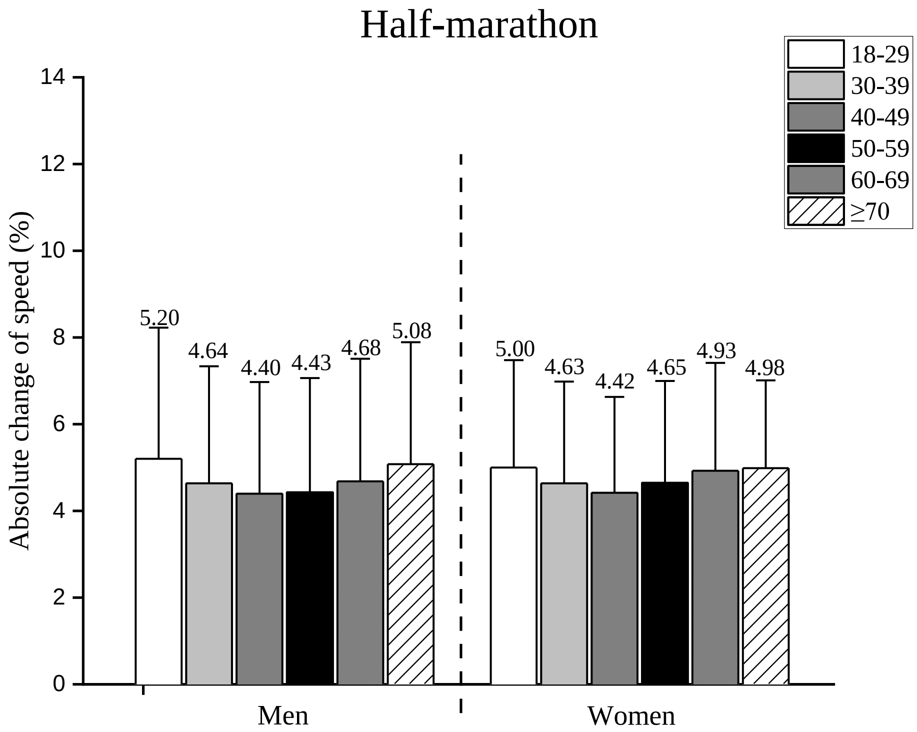


Figure 16. Absolute change of speed in men's and women's half-marathon runners.

The data indicate that the youngest age groups of both sexes significantly differ in ACS from all other age groups up to the age of 69 and in female runners up to the age of 59 (Table 12). However, among males, the older age group of 60–69 did not differ from the middle-aged group of 30–39, and the second middle-aged group of 40–49 did not differ from the quite older age group of 50–59. These results among male runners show the smallest ACS in the age range of 40–59, which includes some older ages as well, while the highest ACS values were observed in runners aged up to 30 and older than 69. Among female runners, the middle-aged group of 30–39 did not differ from the quite older group of 50–59, while the middle-aged group of 40–49 differed from all age groups up to 69. The oldest age group of females did not significantly differ from any other age group. This lack of significance may be attributed to the smallest number of participants in the oldest age group (N = 97).

Table 12. *Pairwise comparisons of absolute change of speed (ACS) between age groups in the half-marathon, separately for men and women.*

Half-marathon			
Age group		Men	Women
		p	
18–29	30–39	**<0.001**	**<0.001**
	40–49	**<0.001**	**<0.001**
	50–59	**<0.001**	**<0.001**
	60–69	**<0.001**	1.000
	≥70	1.000	1.000
30–39	40–49	**<0.001**	**<0.001**
	50–59	**<0.001**	1.000
	60–69	1.000	**0.003**
	≥70	**<0.001**	0.749
40–49	50–59	1.000	**<0.001**
	60–69	**<0.001**	**<0.001**
	≥70	**<0.001**	0.071
50–59	60–69	**<0.001**	**0.008**
	≥70	**<0.001**	0.792
60–69	≥70	**0.002**	1.000

Bold values are statistically significant at a level of <0.05.

6.3. Analysis of Pacing Strategies in the Marathon

To examine Hypothesis 3, the pace profile of all participants in the marathon is presented in Figure 17. Additionally, repeated analyses of variance were conducted to explore the differences between each segment's mean speed. There was a significant difference, Wilks' $\Lambda = 0.37$, $F(4, 82811) = 35382$, $p < 0.001$, $\eta^2 = 0.435$. All marathoners exhibit a decrease in speed up to the fifth segment, followed by an increase in the fifth segment, indicating a noticeable ES. Post-hoc comparisons using the Bonferroni test revealed significant differences between all segments, with a significance level of $p < 0.001$.

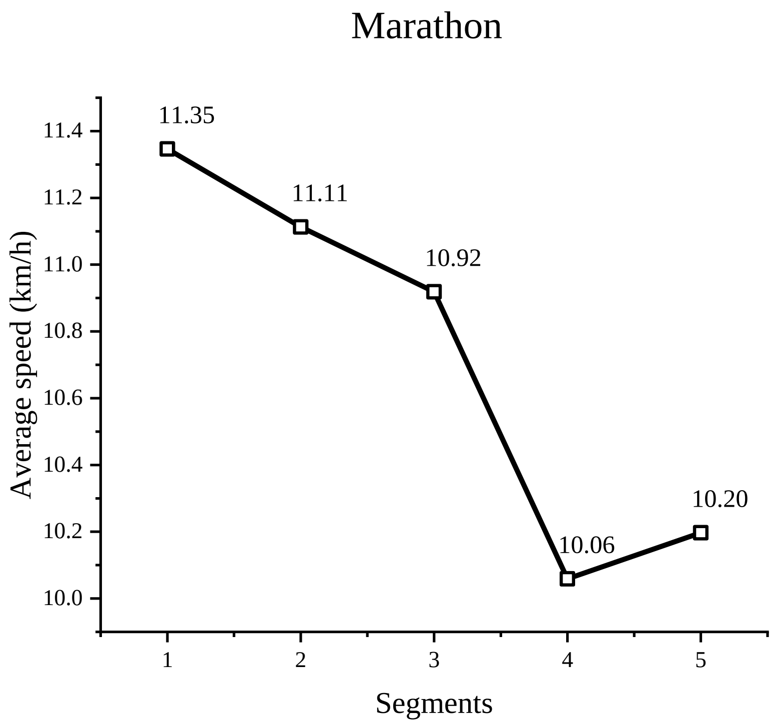


Figure 17. The average speed in each race segment of all participants in the half-marathon.

6.3.1. Analysis of Pacing Strategies Based on Performance Level

To examine Hypothesis 3a, a mixed between-within subjects ANOVA was conducted to assess the impact of performance level on participants' average change of speed across five race segments (Figures 18 and 19). Regarding only men marathon runners (Figure 18), there was a significant interaction between performance level and segment CS, Wilks' $\Lambda = 0.92$, $F(12, 177559) = 499.2$, $p < 0.001$, with a small effect size, $\eta^2 = 0.012$. There was a substantial main effect for segment CS, Wilks' $\Lambda = 0.39$, $F(4, 67111) = 28697$, $p < 0.001$, $\eta^2 = 0.138$. Specifically, most performance groups of runners exhibit a decrease in speed variability up to the fourth segment, followed by a negative increase in the fourth segment, and then another decrease in the fifth segment, indicating the presence of an ES. The only exception was the HL group, where a negative increase in speed variability was observed in the fifth segment as well, indicating the absence of an ES. The main effect comparing performance groups was significant, $F(3, 67114) = 3019$, $p < 0.001$, with a small effect size, almost reaching the threshold for a medium effect, $\eta^2 = 0.055$. Post-hoc comparisons using the Bonferroni test revealed significant differences in all performance groups between each segment CS, with a significance level of $p < 0.001$, except between the fourth and fifth segments in the MLL group, where no significance was shown ($p = 0.089$).

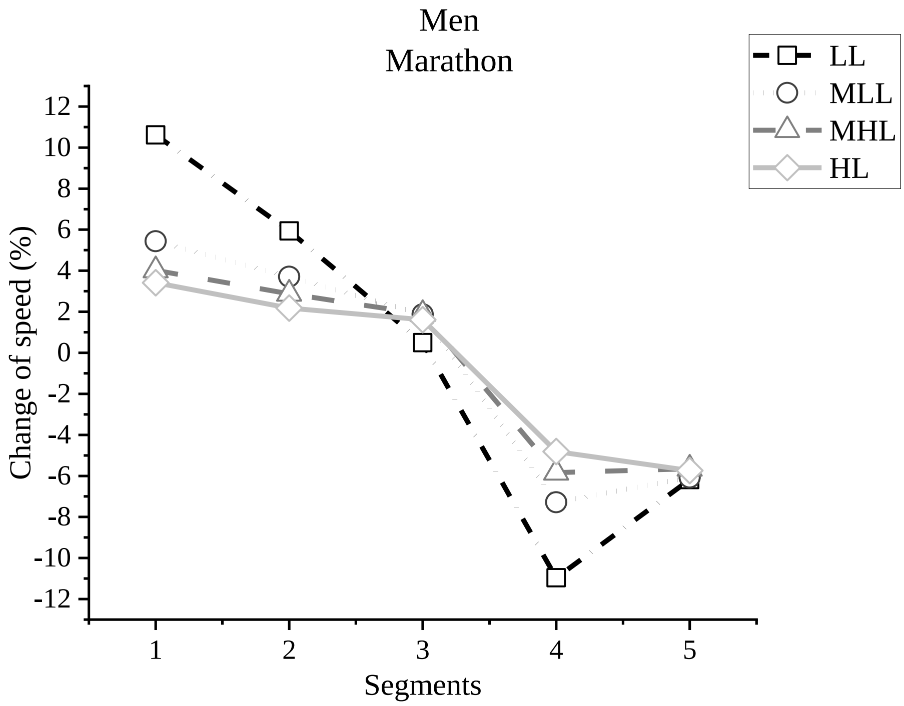


Figure 18. The average change of speed in each race segment of men in the marathon.
Performance groups: LL – Low-Level; MLL – Moderate to Low-Level; MHL – Moderate to High-Level; HL – High-Level.

Regarding only female marathon runners (Figure 19), there was a significant interaction between performance level and segment CS, Wilks' $\Lambda = 0.93$, $F(12, 41512) = 92.92$, $p < 0.001$, however with very small effect size, almost reaching the threshold for a small effect, $\eta^2 = 0.009$. There was a substantial main effect for segment CS, Wilks' $\Lambda = 0.41$, $F(4, 15690) = 5632$, $p < 0.001$, $\eta^2 = 0.169$. Namely, all performance groups of runners exhibit a decrease in speed variability up to the fourth segment, followed by a negative increase in the fourth segment, and then another decrease in the fifth segment, indicating the presence of an ES. The main effect comparing performance groups was significant, $F(3, 15693) = 757.3$, $p < 0.001$, but with a small effect size, $\eta^2 = 0.046$. Post-hoc comparisons using the Bonferroni test revealed significant differences in almost all performance groups between each segment CS, with a significance level of $p < 0.001$ and some of them with $p < 0.01$. Only between the fourth and fifth segment in the MHL group, and between the first and fourth segment in the LL group, no significance was shown ($p = 0.437$ and $p = 0.186$, respectively). The lack of a significant difference between the first and fourth segments observed in the LL group of female participants was due to the statistical procedures that analyzed only absolute (positive) values. However, in the figures, real values were taken into account, including negative values.

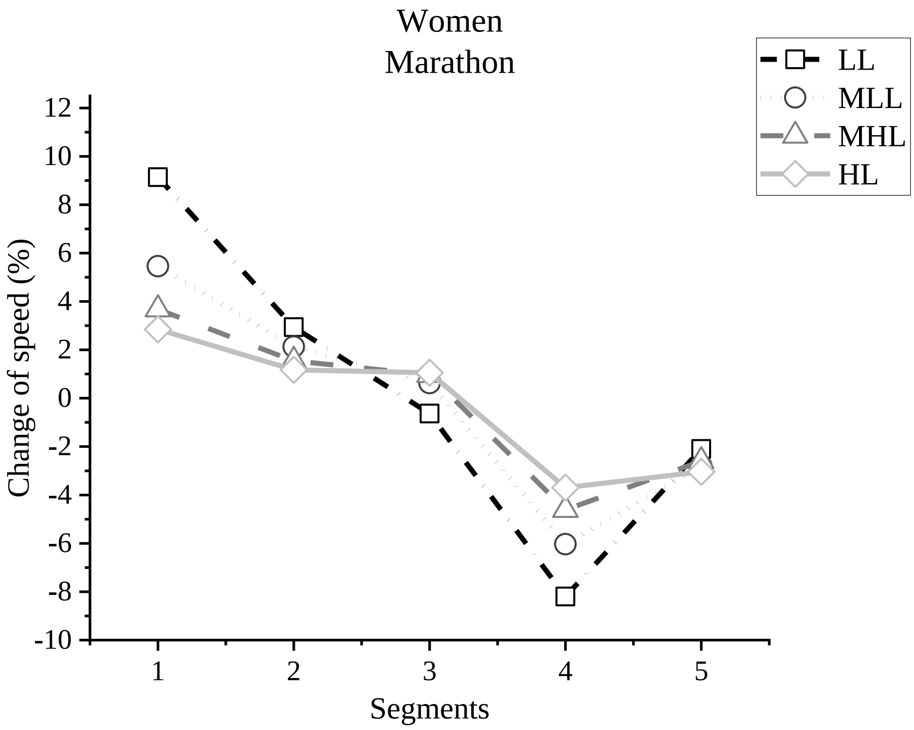


Figure 19. The average change of speed in each race segment of women in the marathon.
Performance groups: LL – Low-Level; MLL – Moderate to Low-Level; MHL – Moderate to High-Level; HL – High-Level.

Following the second part of Hypothesis 3a, a two-way between-groups ANOVA was conducted to explore the impact of performance level and sex on ACS in the marathon (Figure 20). The interaction effect between performance level and sex was significant, F (3, 82807) = 6.80, $p < 0.001$, with the effect size, however, being negligible, $ŋ^2 = 0.000$. There was a significant main effect for performance level, F (3, 82807) = 2803, $p < 0.001$, with medium effect size, $ŋ^2 = 0.091$. Post-hoc comparisons using the Bonferroni test show that all performance groups inside of each sex differ significantly from each other ($p < 0.001$). The main effect for sex was significant, F (1, 82807) = 1460, $p < 0.001$, but with small effect size, $ŋ^2 = 0.016$. Also, post-hoc comparisons using the Bonferroni test show that in each performance group, male and female participants differ significantly from each other at a significance level of $p < 0.001$.

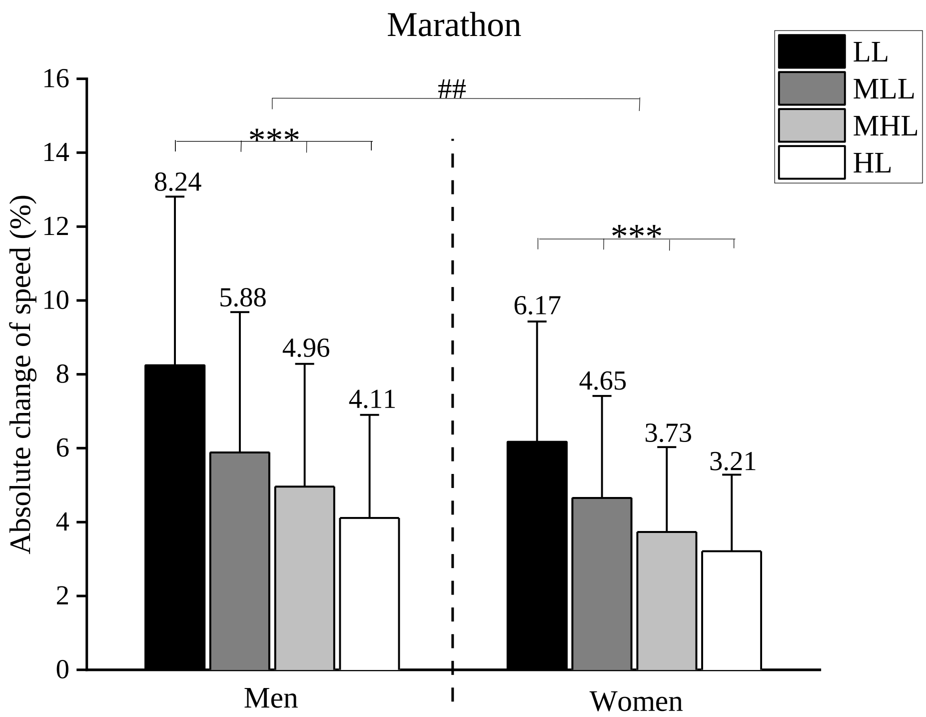


Figure 20. Absolute change of speed in men's and women's marathon runners.
Performance groups: LL – Low-Level; MLL – Moderate to Low-Level; MHL – Moderate to High-Level; HL – High-Level. Error bars represent standard deviation. *** p < 0.001; ### p < 0.001

6.3.2. Analysis of Pacing Strategies Based on Sex

To examine Hypothesis 3b, a mixed between-within subjects ANOVA was conducted to assess the impact of sex on participants' average change of speed across five race segments in the marathon (Figure 21). There was a significant interaction between sex and segment CS, Wilks' $\Lambda = 0.98$, $F(4, 82810) = 393.2$, $p < 0.001$. However, the effect size was very small, $\eta^2 = 0.002$. There was a substantial main effect for segment CS, Wilks' $\Lambda = 0.49$, $F(4, 82810) = 21683$, $p < 0.001$, with medium effect size, $\eta^2 = 0.096$. Both sexes showed a decrease in speed variability up to the fourth segment, followed by a negative increase in the fourth segment, and then another decrease in the fifth segment, indicating the presence of an ES. Post-hoc comparisons using the Bonferroni test show significant differences between each segment inside of each sex, with a significance level of $p < 0.001$, except among female participants between the first and fifth segments, where the difference is not significant ($p = 0.424$). The main effect comparing sexes was significant, $F(1, 82813) = 1465$, $p < 0.001$, but with a very small effect size, $\eta^2 = 0.008$. Additionally, post-hoc comparisons using the Bonferroni test revealed significant differences between sexes inside each segment, with a significance level of $p < 0.001$.

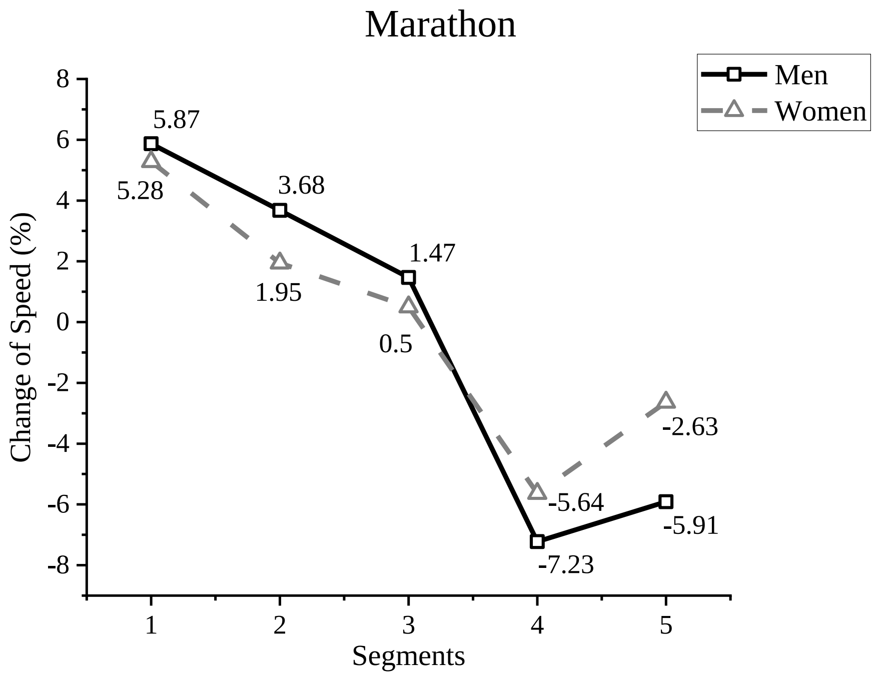


Figure 21. The average change of speed for each race segment in men's and women's marathon runners.

6.3.3. Analysis of Pacing Strategies Based on Age

To examine Hypothesis 3c, a mixed between-within subjects ANOVA was conducted to assess the impact of age group on participants' average change of speed across five race segments (Figures 22 and 23). Regarding only male marathon runners (Figure 22), there was a significant interaction between age group and segment CS, Wilks' $\Lambda = 0.98$, $F(20, 222576) = 72.23$, $p < 0.001$, however with very small effect size, $\eta^2 = 0.003$. There was a substantial main effect for segment CS, Wilks' $\Lambda = 0.81$, $F(4, 67109) = 3980$, $p < 0.001$, but with a small effect size, $\eta^2 = 0.023$. All age groups of runners show a a decrease in speed variability up to the fourth segment, followed by a negative increase in the fourth segment, and then another decrease in the fifth segment, indicating the presence of an ES. Post-hoc comparisons using the Bonferroni test show significant differences in mostly age groups between each segment CS, with a significance level of $p < 0.001$ and a few of them with $p < 0.05$. The difference was not significant between some segments in the 18–29, 60–69 and in the ≥70 age group (Table 13). The main effect comparing age groups was significant, $F(5, 67112) = 68.53$, $p < 0.001$, but with a very small effect size, $\eta^2 = 0.003$. Post-hoc comparisons using the Bonferroni test revealed significant differences between most age groups within each segment up to the fifth one, with a significance level of $p < 0.001$. Some of these differences also reached significance levels of $p < 0.01$ or $p < 0.05$, while others were not significant (Table 14). In the fifth segment, most age groups did not have significant differences between each other ($p > 0.05$) (Table 14).

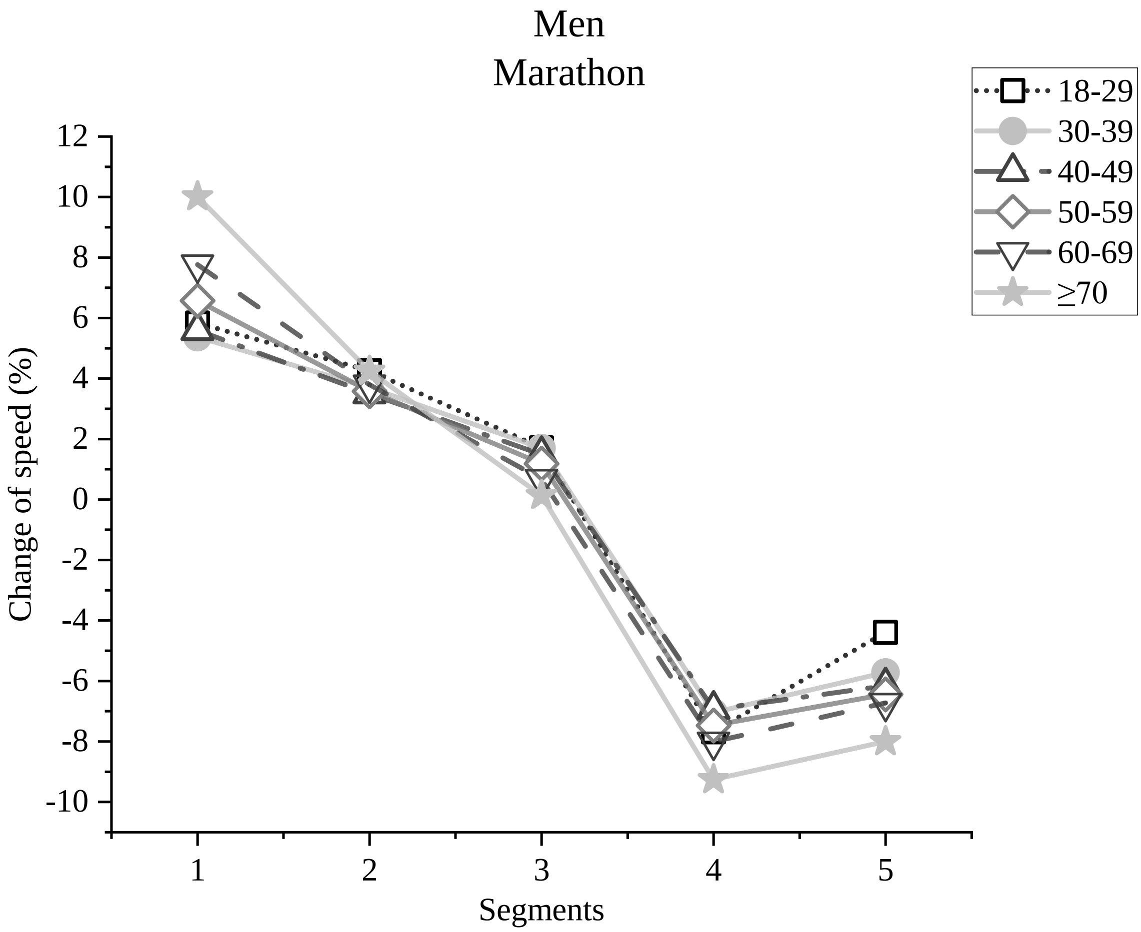


Figure 22. The average change of speed for each race segment in age groups of men's marathon runners.

By observing Figure 22, we can notice that among male runners, the age group of 30–39 displayed the lowest CS in the first segment, at 5.37%, while the highest CS was observed in the oldest group, at 10%. Different results were observed in the second segment, where the 40–49 age group had the lowest CS, while the youngest group had the highest CS (ranging from 3.49% to 4.25%). In the third segment, all age groups showed speeds closest to the average race speed. The oldest group demonstrated the lowest CS, at 0.13%, which increased as the age group got younger, reaching 1.7% in the youngest group. The 40–49 age group showed the lowest CS in the fourth segment, at –6.94%, while the CS increased as the age group got younger and older, reaching –9.26% in the oldest group. In the fifth segment, the youngest group showed the lowest CS, at –4.39%, while the CS increased as the age group got older, reaching –8% in the oldest group. The lower negative values of CS in the fifth segment compared to the fourth segment indicate that all groups demonstrate an ES.

Regarding only female marathon runners (Figure 23), there was a significant interaction between age group and segment CS, Wilks' $\Lambda = 0.98$, $F(20, 52032) = 13.59$, $p < 0.001$. However, the effect size was very small, $\eta^2 = 0.003$. There was a substantial main effect for segment CS, Wilks' $\Lambda = 0.94$, $F(4, 15688) = 249.1$, $p < 0.001$, also with very small effect size, almost reaching the threshold for a small effect, $\eta^2 = 0.009$. All age groups of runners show a a decrease in speed variability up to the fourth segment, followed by a negative increase in the fourth segment, and then another decrease in the fifth segment, indicating the presence of an ES. Post-hoc comparisons using the Bonferroni test show significant differences in all age groups between each segment CS up to the group 60–69, with a significance level of $p < 0.001$, $p < 0.01$ and $p < 0.05$. Significant and non-significant differences in the age groups of 60–69 and ≥70 are shown in Table 13. The main effect comparing age groups was significant, $F(5, 15691) = 27.69$, $p < 0.001$, but with a very small effect size, $\eta^2 = 0.004$, suggesting little practical significance (Cohen, 1988, pp. 284–288). Post-hoc comparisons using the

Bonferroni test revealed significant differences between most age groups within the first and fourth segments, with a significance level of $p < 0.001$. Some of these differences also reached significance levels of $p < 0.01$ or $p < 0.05$, while others were not significant (Table 14).

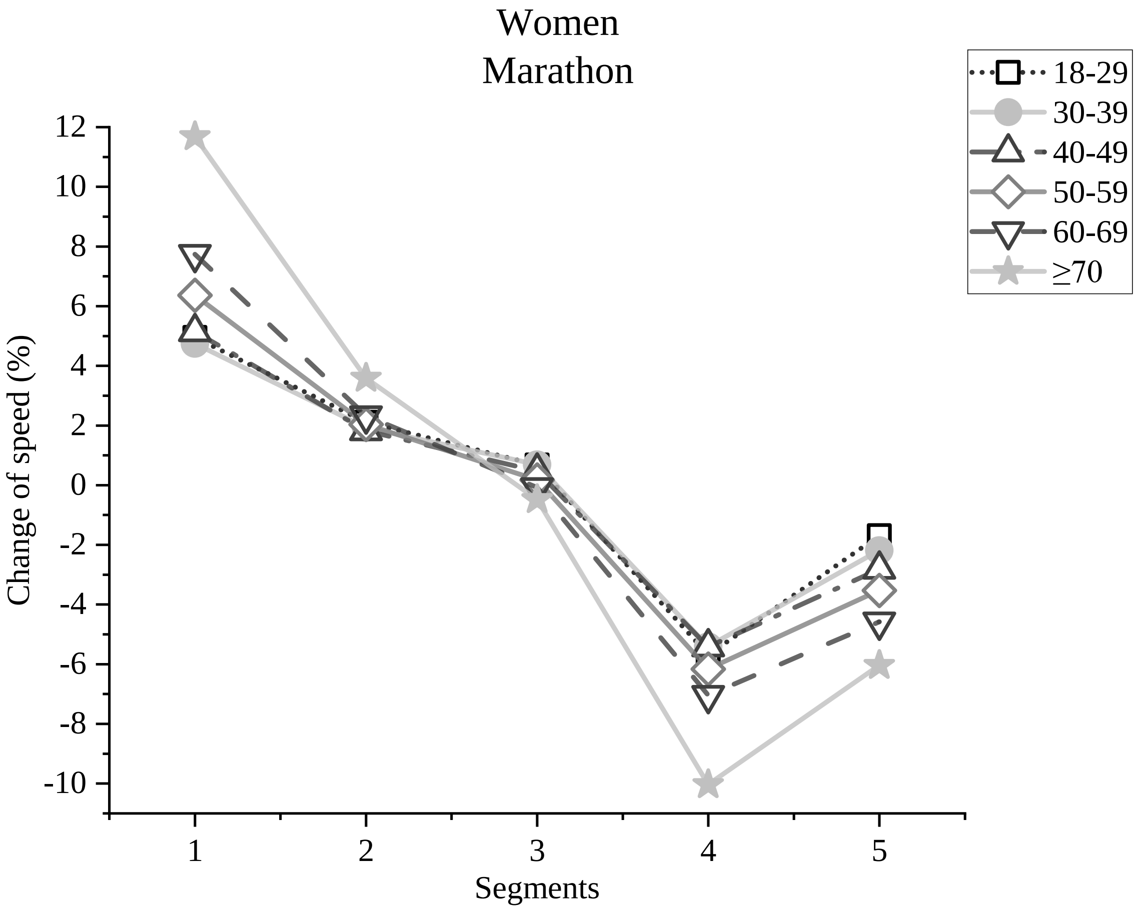


Figure 23. The average change of speed for each race segment in age groups of women's marathon runners.

By observing Figure 23, we can notice that among female runners, the age group of 30–39 exhibited the lowest CS in the first segment, at 4.74%, while the highest CS was observed in the oldest group, reaching 11.68%. Quite different results were observed in the second segment, where the 40–49 age group had the lowest CS, while the oldest group also had the highest CS (ranging from 1.81% to 3.59%). In the third segment, all age groups showed speeds closest to the average race speed, with only the two oldest age groups falling below it (60–69 reached –0.08% and ≥70 reached –0.48%), and the highest positive value was observed in the 30–39 age group (0.69%). The 30–39 age group displayed the lowest CS in the fourth segment, at –5.41%, while the CS increased as the age group got younger and older, reaching –10% in the oldest group. A similar pattern was observed in the fifth segment, where the youngest group showed the lowest CS (–1.69%), while the CS increased as the group got older, reaching –6% in the oldest group. Since lower negative CS values were observed in the fifth segment compared to the fourth segment, it can be concluded that all age groups exhibited an ES. Furthermore, female runners demonstrated a more pronounced ES compared to males.

Only non-significant differences were found in the youngest age group of male runners between the fourth and fifth segments, as well as between some segments in the two oldest groups of both sexes (Table 13). However, the non-significant differences in the oldest groups between the first and fourth segments among female runners and the first and fifth segments among males were attributed to the use of only positive values for statistical analysis, while the figures presented real values (including negative values). Additionally, the smallest number of participants was in the oldest groups, which may have impacted the significance. Considering that Figure 23 shows the highest speed variability in the oldest runners compared to other age groups of female runners, it is intriguing that more non-significant differences between segments were found. However, this lack of significance could be attributed to a very small number of participants (N = 18).

Table 13. *Pairwise comparisons of average change of speed in each segment ($CS_{1–5}$) among the youngest and the two oldest age groups in the marathon, separately for men and women.*

Marathon				
Age group	**Segment**		**Men**	**Women**
			p	
18–29	1	2	**<0.001**	**<0.001**
		3	**<0.001**	**<0.001**
		4	**<0.001**	**<0.001**
		5	**<0.001**	**0.003**
	2	3	**<0.001**	**<0.001**
		4	**<0.001**	**<0.001**
		5	**<0.001**	**<0.001**
	3	4	**<0.001**	**<0.001**
		5	**<0.001**	**<0.001**
	4	5	1.000	**0.001**
60–69	1	2	**<0.001**	**<0.001**
		3	**<0.001**	**<0.001**
		4	**<0.001**	1.000
		5	1.000	**<0.001**
	2	3	**<0.001**	**<0.001**
		4	**<0.001**	**<0.001**
		5	**<0.001**	**<0.001**
	3	4	**<0.001**	**<0.001**
		5	**<0.001**	**<0.001**
	4	5	**<0.001**	**<0.001**
≥70	1	2	**<0.001**	**<0.001**
		3	**<0.001**	**<0.001**
		4	1.000	1.000
		5	**0.017**	**0.005**
	2	3	**<0.001**	1.000
		4	**<0.001**	**<0.001**
		5	**<0.001**	1.000
	3	4	**<0.001**	**<0.001**
		5	**<0.001**	0.649
	4	5	**0.019**	**0.020**

Bold values are statistically significant at a level of <0.05.

The fifth segment CS exhibited the fewest significant differences between age groups, especially in male runners (Table 14), suggesting a similar ES between most age groups. Specifically, among male runners, only differences in CS were found between the runners aged 18–29 compared to runners aged 30–49 and the oldest group compared to runners aged 30–49. Among female runners, significant differences between age groups were observed in the first and fourth segments, while smaller significance was noticed in the other segments (Table 14). In the fifth segment of female runners, no significant difference was found between CS of the age groups 30–39 and the oldest one with any other age group. However, the age group of 40–49 had a significant difference from both age groups of 50–69 and 18–29. As noticed in Figure 23, the first three youngest groups exhibited similar CS through all race segments except in the ES, where it was slightly lower in runners aged 40–49.

Table 14. *Pairwise comparisons of average change of speed in each segment ($CS_{1–5}$) between age groups in the marathon, separately for men and women.*

Marathon		Segment 1		Segment 2		Segment 3		Segment 4		Segment 5	
		Men	Women	Men	Women	Men	Women	Men	Women	Men	Women
Age group		p									
18–29	30–39	**<0.001**	0.119	**<0.001**	**0.007**	**<0.001**	**<0.001**	**<0.001**	**0.028**	**0.003**	0.062
	40–49	**<0.001**	1.000	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	1.000	**0.016**	**<0.001**
	50–59	**<0.001**	**<0.001**	**<0.001**	0.923	**<0.001**	**<0.001**	1.000	**<0.001**	0.161	1.000
	60–69	**<0.001**	**<0.001**	**<0.001**	1.000	**<0.001**	0.128	**<0.001**	**<0.001**	1.000	1.000
	≥70	**<0.001**	**<0.001**	1.000	1.000	**0.023**	1.000	**<0.001**	**0.024**	0.359	1.000
30–39	40–49	**0.008**	**<0.001**	**0.001**	0.238	**<0.001**	0.902	1.000	0.544	1.000	0.405
	50–59	**<0.001**	**<0.001**	1.000	1.000	**<0.001**	1.000	**<0.001**	**<0.001**	1.000	0.304
	60–69	**<0.001**	**<0.001**	0.297	0.273	**<0.001**	1.000	**<0.001**	**<0.001**	0.090	0.244
	≥70	**<0.001**	**<0.001**	**<0.001**	0.432	1.000	1.000	**<0.001**	**0.007**	**0.028**	1.000
40–49	50–59	**<0.001**	**<0.001**	**<0.001**	**0.005**	1.000	0.235	**<0.001**	**<0.001**	1.000	**<0.001**
	60–69	**<0.001**	**<0.001**	**<0.001**	**0.015**	1.000	1.000	**<0.001**	**<0.001**	0.246	**0.017**
	≥70	**<0.001**	**0.001**	**<0.001**	0.248	1.000	0.908	**<0.001**	**0.014**	**0.042**	1.000
50–59	60–69	**<0.001**	**<0.001**	1.000	1.000	1.000	1.000	**<0.001**	**<0.001**	0.681	1.000
	≥70	**<0.001**	**0.022**	**0.001**	0.640	1.000	1.000	**<0.001**	0.130	0.061	1.000
60–69	≥70	**<0.001**	0.651	**0.015**	1.000	1.000	1.000	**0.002**	1.000	0.523	1.000

Bold values are statistically significant at a level of <0.05.

Following the second part of Hypothesis 3c, a two-way between-groups ANOVA was conducted to explore the impact of sex and age group on ACS in marathon runners (Figure 24). The interaction effect between sex and age group was significant, $F (5, 82803) = 7.88$, $p < 0.001$. The effect size was, however, negligible, $\eta^2 = 0.000$. There was a significant main effect for sex, $F (1, 82803) = 33.19$, $p < 0.001$, but also with a negligible effect size, $\eta^2 = 0.000$. Post-hoc comparisons using the Bonferroni test revealed significant differences between sexes in mostly all age groups, with a significance level of $p < 0.001$, except the 60–69 group where the significance level was $p < 0.01$ and in the ≥70 group where no significance was shown ($p = 0.997$). The lowest participation rates in the oldest age groups (males, N = 291; females, N = 18) may have influenced the significance of the findings. Additionally, the main effect for the age group was significant, $F (5, 82803) = 67.93$, $p < 0.001$, but with a very small effect size as well, $\eta^2 = 0.004$. Post-hoc comparisons using the Bonferroni test revealed significant differences between most age groups within each sex, with a significance level of $p < 0.001$. Some of these differences also reached significance levels of $p < 0.01$ or $p < 0.05$, while others were not significant.

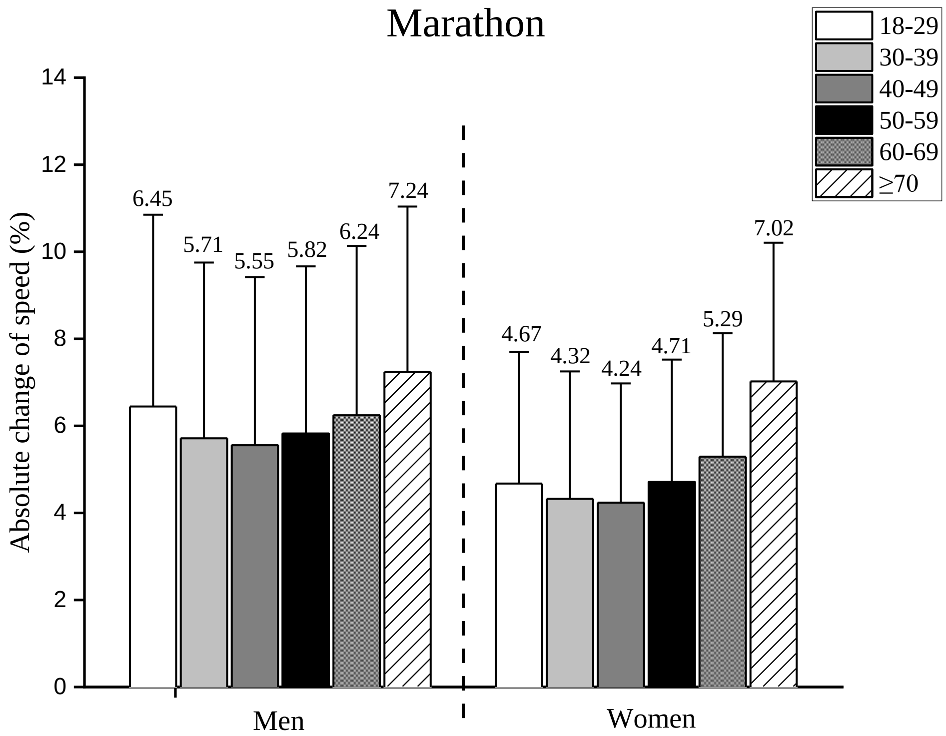


Figure 24. Absolute change of speed in men's and women's marathon runners.

In male runners, the oldest age group significantly differed from all other age groups, while the group aged 60–69 differed from all ages older than 29. However, there was no significant difference between the group aged 50–59 and any other age group as well. Additionally, the two middle-aged groups (30–39 and 40–49) did not differ from each other (p = 0.122). The same non-significant difference was found for these middle-aged groups among female runners as well (p = 1). However, the oldest age group among female runners showed a significant difference from all ages up to age 49, whereas the youngest group showed a significant difference from all age groups except the group aged 50–59 (p = 1). These findings indicate that the two middle-aged groups of 30–49, among both sexes, have a more evenly pace compared to the youngest age group and runners older than age 49.

Table 15. *Pairwise comparisons of absolute change of speed (ACS) between age groups in the marathon, separately for men and women.*

Marathon			
Age group		**Men**	**Women**
		p	
18–29	30–39	**<0.001**	**<0.001**
	40–49	**<0.001**	**<0.001**
	50–59	**<0.001**	1.000
	60–69	1.000	**<0.001**
	≥70	**<0.001**	**0.039**
30–39	40–49	0.122	1.000
	50–59	**<0.001**	**<0.001**
	60–69	**<0.001**	**<0.001**
	≥70	**<0.001**	**0.006**
40–49	50–59	**<0.001**	**<0.001**
	60–69	**<0.001**	**<0.001**
	≥70	**<0.001**	**0.005**
50–59	60–69	**<0.001**	**0.001**
	≥70	**<0.001**	0.071
60–69	≥70	**<0.001**	0.953

Bold values are statistically significant at a level of <0.05.

7. DISCUSSION

The main findings of our study are as follows:

1. Positive PS with an ES and each segment differing from the next one was observed in almost all runners' subgroups, regardless of the race type, performance group, sex and age.
2. Faster runners exhibited a more consistent PS compared to slower runners in both races and sexes, as indicated by the substantial practical significance of performance group influence on ACS. Additionally, slower runners showed a higher ES compared to faster runners.
3. Significant differences between races were observed within each performance group. Each performance group of male half-marathon runners demonstrated a more evenly distributed PS compared to marathon runners, while an opposite situation was observed in female runners. Nevertheless, the difference in ACS between races was of minimal importance in both sexes.
4. Male runners exhibited lower speed variability in the half-marathon race compared to female runners, while the opposite was observed in the marathon. Furthermore, the differences between sexes were greater in the marathon compared to the half-marathon, but the difference between the races had minimal practical significance. Female runners also exhibited a higher ES compared to male runners, regardless of the race, but all differences between sexes had trivial practical significance.
5. Male runners aged 40–59 and female runners aged 40–49 showed a more evenly distributed PS compared to younger and older runners in the half-marathon. In the marathon, the runners aged 30–49 showed a more evenly distributed PS than younger and older runners, regardless of sex. Among male runners, a more consistent PS was observed in the half-marathon compared to the marathon within each age group. However, all these differences had minimal practical significance. Female runners did not show a significant difference in speed variability between the races.
6. The youngest age group exhibited the most pronounced ES in both sexes in the half-marathon, with females showing a more pronounced effect. In the marathon, the youngest group of male runners showed the most pronounced ES, while both the oldest and youngest groups of female runners exhibited a higher ES compared to the other age groups.
7. Female runners aged 40–69 exhibited higher speed variability in the half-marathon compared to male runners, while in the 30–39 age group, male runners showed slightly more pronounced speed changes than female runners. In the marathon race, male runners showed more speed variations than female runners across all age groups up to 69 years. Nevertheless, all of these differences had minimal practical significance.

7.1. Comparison of Pacing Strategies in the Half-Marathon and Marathon

Research aim 1 was to compare PSs among half-marathon and marathon runners in an overall sample. A positive PS with an ES was observed in both races. The influence of the segment CS was found to have a large practical significance, with only a non-significant difference observed between the fourth and fifth segments of the marathon. We obtained partial validation for Hypothesis 1, which suggests that the pacing of half-marathon runners is more evenly distributed compared to the pacing of marathon runners. This validation is based on the significant difference observed in ACS, although the practical significance of this difference was found to be trivial.

The substantial decline in speed during the fourth segment across the overall sample can be attributed to the accumulation of fatigue resulting from the rapid initial pace and the extensive distance covered (Cuk, Nikolaidis, & Knechtle, 2019; Hanley, 2015). The greater ES observed in half-marathoners compared to marathoners might therefore be attributed to the lower level of accumulated fatigue during the shorter race in comparison to the longer one. The excessive rate of acceleration applied at the end could result in a squandered amount of kinetic energy that could be more effectively utilized to achieve a faster pace earlier, leading to an earlier finish and better result (Foster et al., 2023). Based on our findings about a more pronounced ES and a lower average race speed in the shorter race compared to the longer one (as seen in Tables 3 and 4), we can assume that in contrast to the marathon sample, a higher percentage of half-marathon participants were beginners and recreational runners.

According to some authors (Del Coso et al., 2013, 2017), the progressive decline in marathon running speed can be attributed to the development of moderate to severe muscle damage caused by running. Muscle strain in the legs is identified as one of the major negative outcomes in both races (ibid.). Marathon runners experienced more pronounced muscle strain compared to half-marathon runners (Del Coso et al., 2017). This finding may help explain the more consistent PS observed in the shorter race compared to the longer one in our study. It is important to note, however, that the majority of participants were male runners, who naturally possess a higher proportion of type 2 muscle fibers (Nuzzo, 2023, 2024) compared to female runners. This difference in muscle fiber composition may increase the risk of glycogen depletion and speed decrease during races lasting approximately two hours (Impey et al., 2020; Joyner & Coyle, 2008). This additional factor may further explain the greater speed decrease observed in the last segments of the marathon race and the ACS compared to the half-marathon.

7.1.1. Comparison Based on Performance Level

The research aim 1a was to compare PSs among half-marathon and marathon runners based on their performance levels. Our findings demonstrated a large influence of performance level on participants' overall speed variability across the races in both sexes. Specifically, faster runners displayed more even PS compared to slower runners. Regarding male runners in each performance group, half-marathoners demonstrated a more consistent PS compared to marathoners, while among females, the situation was the opposite. Nevertheless, the difference in ACS between races was of minimal importance in both sexes. Based on these results, Hypothesis 1a, according to which the pacing of half-marathon runners is more evenly distributed compared to the pacing of marathon runners in all performance groups of both sexes, is partially validated.

A recently published study by Ristanović et al. (2023) focused on the same theme and employed a sample size comparable to the one utilized in this thesis. To be specific, the study examined results from half-marathon and marathon races in Vienna over the period of 13 years (2006–2018). As a result, the study arrived at similar, albeit not identical, conclusions regarding the comparison of PS between half-marathon and marathon races concerning the performance level of runners.

We observed positive PSs in all performance groups of male and female runners in both the marathon and half-marathon races (Tables 3 and 4). The most significant decrease in speed was noticed in the fourth segment, particularly among slower groups. The same result was observed in the study conducted by Ristanović et al. (2023), despite having a slightly smaller sample size. This is particularly intriguing as this thesis utilized the same sample size, but incorporated results from races conducted between 2019 and 2023, which encompassed the post-COVID-19 period. It has been suggested that the COVID-19 pandemic, which had a global impact, could indirectly influence performance and PSs (Çelen, 2023; Mulcahey et al., 2020; Valenzuela et al., 2021). In light of this, it can be inferred that the pandemic likely had an insignificant impact on the overall PS within our sample. However, this can be attributed to the fact that the additional participants constituted a relatively small portion of the total sample, specifically 24,323 runners, representing only 12%. As such, this may not be sufficient to yield statistically significant differences in this variable. On the contrary, the differences between half-marathon and marathon among performance groups in females also had small practical significance, but half-marathoners exhibited a more consistent PS compared to marathoners. Considering that in this study, the difference between races among female runners was significantly smaller compared to male runners, one might entertain doubts. However, the current study, conducted on a larger sample, confirmed not only the small practical significance of that difference but also revealed an even higher ACS in the half-marathon compared to the marathon.

Notably, both male and female runners in all performance groups achieved faster average race times in the marathon than in the half-marathon. This finding is consistent with a study that analyzed over 70,000 race finishers in Chinese races (Yang et al., 2022). Since our sample of half-marathoners had 81% more participants than in marathon (150,232 vs. 82,815), these results can be explained by the fact that an increased number of runners can negatively impact results (Stojiljković et al., 2022; Vitti et al., 2020). It is plausible to assume that a larger proportion of half-marathon participants consists of recreational and beginner runners compared to the marathon. Intriguing, the half-marathon to marathon ratio is approximately 3:1 for females and close to 2:1 for males. Furthermore, previous running experience can influence endurance performance (Voight et al., 2011). Given the greater accessibility of the half-marathon, as it is a shorter distance which might attract more participants, it can be inferred that a significant number of recreational and inexperienced runners taking part contributed to the overall decrease in average race speed.

Intriguingly, across all performance groups, male runners exhibited a faster average speed in each segment up to the third one during the marathon, in contrast to the half-marathon race. However, in the fourth and fifth segments, the situation was reversed, with faster average speeds found in the half-marathon. The ACS among male runners that showed higher pace variability in the marathon compared to the half-marathon, supports these findings. Specifically, male marathoners start the race at a faster pace than male half-marathoners but experience a greater speed decline in the last segments, leading to a higher ACS than in half-marathoners. In all performance groups among female runners, all segments were faster in the marathon compared to the half-marathon, with the exception of the fifth segment. In contrast to male runners, female runners exhibit quite different patterns, showing a smaller difference in ACS within each performance group between the races. The possible cause of the differences between male and female runners can be attributed to physiological factors, rather than psychological and social, which will be explained in the following section.

In general, our study findings suggest that runners with higher performance, regardless of sex and race groups, exhibit less variation in their pace compared to those with lower performance. This conclusion aligns with previous studies that focused specifically on marathon races (Kais et al., 2019; Nikolaidis & Knechtle, 2017). Notably, one research revealed that slower runners, in contrast to their predicted finishing time, experienced a more pronounced decline in pace during the half-marathon, while faster runners maintained a consistent pace (Piacentini et al., 2019). In particular, the intensity of carbohydrate utilization in metabolic processes exhibits a supralinear increase with running intensity (Romijn et al., 1993). The increased depletion of glycogen stores can potentially contribute to decreased intensity, resulting in altered substrate utilization, neuromuscular fatigue, and/or psychological factors related to the RPE (rating of perceived exertion) (Abbiss & Laursen, 2008; Impey et al., 2020). Therefore, maintaining an even pace appears to be the most efficient metabolic strategy for completing a long-distance race (Rapoport, 2010). By considering our results, it can be inferred that higher-performance runners achieved even better outcomes than anticipated due to their consistent pacing. On the other hand, runners who displayed greater fluctuations in running speed experienced higher energy expenditure, resulting in poorer performance (Foster et al., 2023; Rapoport, 2010).

In addition, it is worth noting that climatic conditions and outside temperature can have an impact on pace and performance during long-distance races (Trubee et al., 2014). Furthermore, slower marathon runners and those who are less experienced may have limited knowledge about proper hydration practices and their importance (Namineni et al., 2021). Given that the Vienna races commence in the early morning hours each year, when temperatures are relatively cooler compared to later hours (as mentioned in the methodology section), slower runners consistently finish the race during the warmer part of the day in comparison to faster runners (*Vienna City Marathon*, 2023). It is important to acknowledge that even a minor increase in outside temperatures, such as a 1 °C rise, can have a negative impact on marathon running performance (Knechtle et al., 2019) leading to increased heat stress and decreased speed (Leslie et al., 2023). Therefore, the significant decline in pace observed in our study among slower runners during the race could also be attributed to the rise in outside temperature (Knechtle et al., 2019). A similar rationale can be applied to explain the greater variability in pace observed among marathoners compared to half-marathoners. Half-marathoners, as well as faster runners, tend to spend less time on the course when temperatures are relatively lower.

According to research conducted by St Gibson et al. (2006) and Koning et al. (2011), the knowledge of the race endpoint is the crucial factor in determining the PS. It takes time and experience to acquire the necessary understanding of environmental conditions, internal metabolic functions, and fuel reserves specific to a given race distance (Foster et al., 2023; St Clair Gibson et al., 2006). As a result, it is expected that experienced and faster runners will maintain a more even pace, while those with less experience and lower performance levels tend to exhibit a more pronounced decline in pace (Deaner et al., 2015), which is consistent with the findings of our research.

Across all performance groups, male marathon runners displayed larger variations in speed compared to their counterparts participating in half-marathons. Considering factors such as sex and race, the LL group of male marathon runners demonstrated the highest speed variability (8.24%). A study conducted by Nikolaidis and Knechtle (2018b) revealed that male runners with higher aerobic capacity demonstrated less variation in speed throughout the marathon race. Since higher aerobic capacity is related to improved endurance performance, these factors may contribute to the more consistent PS observed in faster male runners in our study. The same might also impact slower runners, leading them to demonstrate more speed variability, as lower aerobic capacity is associated with poorer results. Accordingly, aerobic capacity may help male runners to resist fatigue during the race.

In contrast, among female runners, each performance group demonstrated lower speed variability in the marathon compared to the half-marathon race. The differences between the races were significant, although they had a small practical significance. One potential explanation for the contrasting results among female runners, in comparison to males, could be attributed to physiological factors (Ansdell et al., 2020; Beltrame et al., 2017; Nuzzo, 2024) rather than psychological (Allen & Dechow, 2023; Dechow & Allen, 2023) and social factors (Proverbio, 2021), as explained in the following section. However, a similar difference between performance groups among male runners can also be observed in females.

7.1.2. Comparison Based on Sex

The research aim 1b was to compare PSs among half-marathon and marathon runners based on sex. Female runners exhibited smaller ACS in the marathon, whereas male runners showed smaller ACS in the half-marathon race. The differences between sexes were greater in the marathon compared to the half-marathon race. However, the differences between sexes and races had a trivial practical significance. Based on these findings, we partially validated Hypothesis 1b, indicating that female runners pace more evenly compared to male runners in both races, with differences greater in the marathon than in the half-marathon.

During both races, for both sexes, a positive PS was observed, with an ES, which was more pronounced in the half-marathon than in the marathon (Table 5). A positive PS was observed in both male and female runners in other studies that examined mass participation events in both half-marathons and marathons (Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis, Ćuk, & Knechtle, 2019). However, some differences were found among elite runners of both sexes (Hanley, 2015, 2016). Elite male runners exhibited positive pacing with an ES in the half-marathon (Hanley, 2015), while the group of medalists demonstrated slightly different patterns. They increased pace in the second segment, maintained it in the third segment, slightly decreased it in the fourth segment, and eventually showed the highest ES. In the same study, all elite female runners exhibited a slight positive pacing with an ES. The fastest elite male marathoners demonstrated a slight increase in speed up to the 15th kilometer, maintained their speed until the 40th km and exhibited a decrease in the last 2,150 m (Hanley, 2016). In contrast, the fastest female marathoners showed a slight speed increase up to the 10th km, followed by a slight decrease up to the 20th km, and then an increase until the end of the race, with a noticeable ES (ibid.). Additionally, one study that examined the PS of lower elite level half-marathoners, a decrease in pace was observed from the fifth km to the end of the race, in both sexes (Stanković et al., 2019). These results are not completely consistent with the results of our study, which could be attributed to factors such as a larger number of participants and worsened average race times (Stojiljković et al., 2022) indicative of a higher representation of recreational runners and beginners.

Intriguingly, in comparison to other studies, an ES has been observed among runners in mass marathon events (Nikolaidis et al., 2019) and in elite female marathoners (Hanley, 2016). However, in elite male marathoners, it was only noticeable in the slowest group (Hanley, 2016). Several studies, including Cuk et al. (2019) with mass participants, and Hanley (2015) with elite runners, have reported the presence of an ES phenomenon in half-marathons. However, other studies did not observe the presence of an ES phenomenon in half-marathons (Nikolaidis et al., 2019; Nikolaidis, Ćuk, & Knechtle, 2019; Stanković et al., 2019). As mentioned in the preceding section, the noticeable surge towards the end of the race indicates the runners' increased caution and preserved energy throughout the race, ensuring they avoid complete exhaustion before reaching the finish line (Koning et al., 2011). The acceleration observed can be attributed to the runners' awareness of the approaching finish line and the decreased risk of not being able to complete the race (ibid.). This knowledge serves as motivation for them to utilize their remaining energy reserves and make a final push (Skorski & Abbiss, 2017).

Surprisingly, the results of our study demonstrated a significantly more evenly distributed pacing in male runners compared to female runners in the half-marathon race (4.64% vs. 4.68%, respectively), but with minimal practical significance. These results are consistent with the findings of the study by Nikolaidis et al. (2019), where a similar PS was observed between sexes in the half-marathon, with female runners exhibiting slightly higher ACS compared to male runners (4.11% and 4.09%, respectively). However, no significant differences between sexes were found in their study. The significance observed in our study could be attributed to the much larger sample size compared to the study of Nikolaidis et al. (2019) (150,232 vs. 7,258, respectively). Slightly different findings were shown in the study by Cuk, Nikolaidis and Knechtle (2019), where the differences between sexes were significantly bigger in marathon than in half-marathon running, but still with female runners pacing more evenly in both races. The reason for this inconsistency in the results may be also attributed to the significantly larger number of participants included in our study (150,232 vs. 11,440). While the study by Cuk, Nikolaidis and Knechtle (2019) only hinted at a doubt that female runners may not pace more evenly than male runners in shorter races, our study, with a larger sample size, revealed even more significant findings. There is evidence showing a growing number of women engaging in running, particularly in shorter distances rather than longer ones (Nikolaidis et al., 2021).

Several authors have observed that with an increase in the number of participants, there is a tendency for average performance to decrease (Reusser et al., 2021; Stojiljković et al., 2022). Consequently, the higher ACS among female half-marathoners compared to male half-marathoners can be attributed to this growing participation of female runners in the race. It can be presumed that a significant proportion of these female runners are beginners and recreationalists, who may lack sufficient experience to sustain an optimal PS (Deaner et al., 2015; Swain et al., 2020).

When it comes to female runners, the difference between half-marathon and marathon is less prominent than in male runners, as we might see in Figure 6. These findings may be connected to previous studies suggesting that female runners exhibit a lower susceptibility to fatigue compared to male runners when engaging in tasks of similar relative intensity (Hunter, 2014, 2016). This could be attributed to their higher proportion of type 1 muscle fibers (Nuzzo, 2023, 2024), resulting in a greater reliance on fat oxidation and a decreased utilization of carbohydrates and amino acids compared to male individuals (Tarnopolsky, 2008). In contrast, male individuals have a higher percentage of type 2 muscle fibers (Nuzzo, 2023, 2024), which require greater utilization of carbohydrates and can lead to muscle glycogen depletion (Impey et al., 2020). As the availability of "fuel" becomes a challenge when the race lasts longer than approximately two hours (Joyner & Coyle, 2008), male runners are more affected in a marathon compared to a half-marathon race. Moreover, this physiological characteristic may account for the significantly faster dynamics of oxygen extraction in peripheral and pulmonary blood during moderate exercise intensities, observed in female individuals compared to male individuals (Beltrame et al., 2017).

Trained female individuals have demonstrated an approximately one-third higher rate of mitochondrial internal respiration, indicating enhanced mitochondrial oxidative function compared to trained male individuals (Cardinale et al., 2018). Overall, female muscle metabolism exhibits a greater capacity for ATP synthesis through oxidative phosphorylation in comparison to male (Ansdell et al., 2020). There is also some evidence suggesting that female individuals are more likely to employ effective strategies that reduce the risk of heat-related illnesses during physical exertion (Périard et al., 2017). Since both races start in the morning hours (9 am), the longer race always lasts longer than the shorter one, and the outside temperature increases (*Vienna City Marathon*, 2023). As a result, female runners may have an advantage in reducing heat stress during the second part of the race compared to male runners (Périard et al., 2017). The aforementioned factors may contribute to the less pronounced differences in speed variability between half-marathon and marathon observed in female runners, while more pronounced in male runners, which suggests that male runners exhibit much higher speed variability in the longer race (Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis, Ćuk, & Knechtle, 2019). Consequently, these physiological characteristics contribute to less pronounced speed variability differences between sexes in the shorter race, compared to the longer one (ibid.). Although these differences provide female runners with certain advantages in longer-distance performance, other factors such as lower oxygen-carrying capacity and a higher body fat percentage counterbalance these potential benefits (Besson et al., 2022). As a result, it is uncommon for female runners to outperform male runners in such scenarios.

There are sex-specific differences in running biomechanics, with females exhibiting greater non-sagittal hip and knee joint motion compared to males, attributed in part to anatomical variations such as wider pelvis, larger femur-tibia angle, and shorter lower limb length relative to total height (Besson et al., 2022). While these factors may contribute to the advantage of male runners in speed maintenance (Oeveren et al., 2024) during the half-marathon race, the absence of sex comparisons in studies on running biomechanics under fatigue conditions is notable. However, as the distance increases and glycogen energy reserves are depleted to a greater extent in males (Beltrame et al., 2017; Impey et al., 2020; Nuzzo, 2024), they lose their biomechanical advantage and experience more significant slowdowns in marathons compared to females. Although this is currently a hypothesis, further research could investigate this topic more extensively.

If we specifically analyze the disparities between sexes concerning marathon races, it is plausible to assume that factors beyond physiology, such as psychological and social factors, may have a more substantial influence on the lower speed variability observed in female runners in comparison to male runners. In previous studies, male runners have demonstrated higher levels of competitiveness (Allen & Dechow, 2023; Dechow & Allen, 2023) and overconfidence (Hubble & Zhao, 2016), suggesting that psychological factors contribute to greater pacing variability throughout the race. Therefore, they often overestimate their capabilities at the start, leading to a greater slowdown compared to female runners. On the other hand, female runners tend to prioritize achieving a specific time goal less (Allen & Dechow, 2023; Dechow & Allen, 2023), but they are internally motivated and health-conscious (Krouse et al., 2011). This may result in less significant slowdowns during the race. Additionally, there is evidence to suggest that female individuals are more inclined to engage in social interactions compared to male individuals (Proverbio, 2021), which could contribute to a more relaxed approach to running and prioritizing enjoyable interactions with other runners.

The results of our study demonstrated that female runners exhibited less speed variability compared to male runners in longer races, while in shorter races, fewer differences between sexes were observed, with even fewer speed variability in males. These findings are largely consistent with the results reported in previous studies that have examined similar topics (Cuk et al., 2021; Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis, Ćuk, & Knechtle, 2019). Based on the aforementioned evidence, it is likely that physiological characteristics, rather than psychological and social factors, play a more significant role in the observed differences between male and female runners in races of varying distances.

It can be observed from Table 5 that the disparity in average race speed between sexes was greater in the half-marathon (1.17 km/h) compared to the marathon (1.01 km/h) distance. This observation aligns with the findings of previous studies that indicate a reduction in the performance gap between sexes in longer races (Nikolaidis et al., 2021; Yang et al., 2022).

In Figure 6, it can be noticed that the ACS of both sexes in the half-marathon and female runners in the marathon were very similar. However, the same variable for male runners participating in the marathon was notably higher than the others. Specifically, the differences between sexes were greater in the marathon compared to the half-marathon, although these differences had little practical significance. These results are not consistent with previous studies that indicated a more even pacing in the half-marathon for both sexes (Cuk, Nikolaidis, & Knechtle, 2019; Cuk et al., 2019; Nikolaidis et al., 2019; Nikolaidis, Ćuk, & Knechtle, 2019). However, our findings partially align with previous studies indicating that female runners tend to maintain a more consistent pace than male runners in marathons, but the pace disparity between sexes was found to be nearly insignificant in half-marathons (Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis, Ćuk, & Knechtle, 2019) and 10 km races (Cuk et al., 2021).

Intriguing, both male and female participants achieved faster times in the marathon compared to the half-marathon (Table 5). This result is consistent with the study of Yang et al. (2022) which showed that the half-marathon was run at a slower pace than the marathon for both sexes. However, one study with results from mass races (Nikolaidis et al., 2019) showed that the category of women in the half-marathon is slower than women in the marathon, while the situation is reversed for men. The analyzed races in their study took place on the same day and it is unlikely that external conditions significantly influenced this outcome in female runners. Considering the findings that average performance tends to decrease as the number of participants increases (Reusser et al., 2021; Stojiljković et al., 2022), the outcome of Nikolaidis et al. (2019) study can be attributed to the nearly eightfold increase in the participation of women in the half-marathon compared to the marathon (8:1), while this ratio among men was 3:1. In contrast to their participant sample, our study observed a participant ratio of approximately 3:1 for women in the half-marathon compared to the marathon, whereas for men the ratio was 2:1. Accordingly, Nikolaidis et al. (2019) analyzed a much higher half-marathon to marathon ratio in female runners compared to our study. This may help explain why we found faster times in the marathon compared to the half-marathon, not only for women but also for men.

Moreover, considering the recent trend of women's participation in these races increasing at a greater rate compared to men (Stojiljković et al., 2019; Yang et al., 2022), it is reasonable to assume that a significant portion of female participants are beginners. The half-marathon, being a shorter and more accessible distance than the marathon, is often the preferred choice for beginners, which may result in poorer performance outcomes. Additionally, recreational runners who seek professional assistance during their training are more prevalent among those preparing for marathons and ultramarathons compared to those preparing for half-marathons (Knechtle, Tanous, et al., 2021). This could be a contributing factor to slower running times in shorter distances compared to longer ones.

7.1.3. Comparison Based on Age

The research aim 1c was to compare PSs among half-marathon and marathon runners based on age. Our findings indicate that age group significantly influences the overall speed variability of participants in both sexes across the races. Middle-to-quite-older-aged male runners (aged 40–59) and middle-aged female runners (aged 40–49) exhibited a more consistent PS compared to younger and older runners in the half-marathon. In contrast, the situation was quite different among both sexes in the marathon, where the middle-aged group (30–49 age) showed a more even PS than younger and older runners. Based on these findings, we can conclude that the specific age groups exhibiting the lowest ACS varied depending on the type of race, but in the half-marathon, it depended on the sex as well. A more evenly distributed PS was observed in the half-marathon compared to the marathon within each age group among male runners. Additionally, the differences between age groups observed in the male marathon runners were a bit greater compared to the male half-marathon runners. However, it is important to note that all of the previously mentioned differences had negligible practical significance. Finally, no significant difference in ACS between races was observed among female runners. Based on these results, we achieved partial validation for Hypothesis 1c, according to which middle-aged runners pace more evenly compared to younger and older runners, with differences greater in the marathon than in the half-marathon.

The age group of 30–39 in the half-marathon race had the highest number of men (N = 29,519), with the next older group having just one male participant less. However, in the marathon race, the age group of 40–49 convincingly had the highest number of male participants. A similar pattern was observed among female runners, with the age group of 30–39 having the highest number of participants in the half-marathon (N = 14,985), while the age group of 40–49 had the highest number in the marathon (N = 5,537). Other studies analyzing mass participant events have also found that age groups with the highest participation in marathons are typically older compared to those in the half-marathon races (Yang et al., 2022). Their study showed a comparison of 41–50 vs. 31–40 age groups among male runners, while among female runners it was 41–50 vs. 26–35.

The results of our study showed a more evenly distributed PS in middle-to-quite-older-aged men and middle-aged women in half-marathon, as well as middle-aged runners of both sexes in marathon, compared to younger and older runners. In the study by Cuk et al. (2019), no differences in pace variability among female runners across different age groups were observed, which is in line with the results of our study. Additionally, the results of our study showed significant and even more noticeable differences in men, but again with little practical significance. In the same study by Cuk et al. (2019), men below the age of 30 and men over 60 years old displayed greater variability in pace compared to other age groups, which is also observed in our study, but with very little practical significance as well.

It is important to mention that Cuk et al. (2019), utilized another variable to describe pacing variability in their study, which they referred to as the “pace range”. Specifically, the “positive range” refers to the percentage deviation of the fastest segment speed from the average race speed, while the “negative range” refers to the percentage deviation of the slowest segment speed from the average race speed.

Finally, the “pace range” is calculated by summing the absolute values of the percentage deviation between the fastest and slowest segments from the average race speed. This method also facilitated the normalization of speed comparisons among runners and between different running distances, as it was used before in the study of Breen et al. (2018). Besides ACS and pace range, the third variable with high reliability used to describe pacing variability is the coefficient of variation (CV) (Cuk et al., 2024).

It can be noticed that ACS between age groups was slightly greater in male marathon runners than in half-marathon runners, while no significant differences between races were observed among female runners. Similar results were observed in the study by Cuk et al. (2019), however, with significant differences observed in female runners as well. Furthermore, with regard to female runners, it is evident that the oldest age group in the marathon exhibits the highest ACS, and this distinction is notably pronounced compared to the other age groups in both races. However, it is worth noting that the differences in ACS between races within the age group of ≥70 displayed a lower level of significance ($p < 0.05$) compared to the other age groups. These differences in results can be attributed to a significantly smaller number of runners (half-marathon, N = 97; marathon, N = 18), in the oldest group compared to the younger ones, which, in statistical procedures, has made all the differences less significant. The oldest group of other studies consisted of 55 and older (Nikolaidis et al., 2019) and 60 and older runners (Cuk, Nikolaidis, & Knechtle, 2019). In this regard, it is important to note that the studies referenced considered a significantly broader range of runners' ages compared to our study. Although the total sample sizes in these studies are much smaller than ours (N = 9,137 and N = 17,465, respectively), the number of participants in the oldest age groups did not differ significantly (women half-marathon, N = 203 and 96; women marathon, N = 12 and 31). Furthermore, these studies examined differences among age groups divided into 5-year intervals, but the oldest age groups encompassed a wider range of ages.

Intriguingly, we observe lower ACS in female marathon age groups compared to female half-marathon in the first three younger age groups (age of 18–49), while in men, all age groups have higher ACS in marathon than in half-marathon. The results of these three younger groups of female runners are not consistent with the results of Cuk et al. (2019), who observed that half-marathon runners of all age groups and both sexes exhibited more even pacing compared to marathon runners. Namely, the results are consistent only with men. Additionally, in the study of Nikolaidis et al. (2019) significant main effects of race were shown in female runners as well as in male runners, indicating more even pacing by both sexes in half-marathon compared to marathon and inconsistency with our results concerning female runners.

In each race and sex group of our study, the lowest ACS was noticed in the age group of 40–49. However, in the total sample, the lowest ACS was noticed in female marathon runners of age 40–49. In contrast, the highest ACS was shown in male marathon runners of age ≥70. In the study conducted by Cuk et al. (2019), the lowest pace range was observed in the female half-marathon age group of 40-44, followed by the 45-49 group, corresponding to the 40-49 age group in our study. In that regard, the results are partially consistent with our findings, with the difference being that in our study, the lowest variability was observed in the same age group but in a different race. In the same study, the highest pace range was observed in the men’s marathon age group of 18–24 and then 25–29, which would correspond to our 18–29 age group. In our study, this age group had the second-highest ACS, following the oldest one (≥70), which is very close to their results. Additionally, if we only count the half-marathon, the highest ACS was observed in the age group of 18–29.

More evenly distributed PS in half-marathons than in marathons observed in male runners suggests that aging plays a larger role as the race distance increases (Nikolaidis et al., 2019). Severe fatigue in the later stages of marathons, caused by glycogen depletion (Coyle, 2007), rather than psychological factors (e.g., a rapid race start driven by a competitive spirit) (Cuk, Nikolaidis, & Knechtle, 2019) may play a greater role in this phenomenon. Younger men, especially those under 30, may exhibit more speed variabilities due to their higher self-esteem, leading to a fast start and overestimation of their abilities (Breen et al., 2018). Less experienced younger runners may struggle with pacing control, resulting in frequent speed changes and rapid fatigue. Setting an effective PS involves factors such as race duration knowledge, internal timing, and memory of past strategies (St Clair Gibson et al., 2006). Younger runners with limited experience may lack a pacing template, while older men tend to run slower, increasing the likelihood of fatigue and pacing variability. Additionally, older runners may have difficulties establishing an optimal PS due to age-related variations in physiological and training characteristics. Namely, the main factor contributing to performance decline is the gradual decrease in VO_2max, estimated at around 10% per decade, resulting from central and peripheral changes (Hawkins & Wiswell, 2003; Tanaka & Seals, 2008). Performance is also influenced by morphological changes such as reduced lean body mass and increased fat infiltration into muscles (Maharam et al., 1999; Visser, 2021). Around age 50, age-related muscle atrophy becomes noticeable, with an annual skeletal muscle mass loss of 0.26% to 0.56% for individuals aged up to 70 (Faulkner et al., 2008; Visser, 2021). The decline in endurance exercise performance stems primarily from decreased exercise intensity and sustainable training volume associated with aging. Consequently, older runners may encounter difficulties in maintaining their training levels as they age.

Our findings indicate that the oldest runners exhibit reduced variations in speed during the half-marathon compared to the youngest age group, whereas the opposite pattern was observed in the marathon. The significantly higher ACS observed in the oldest group of marathon runners, irrespective of sex, may indicate the challenges they face in coping with age-related physical changes (Hawkins & Wiswell, 2003; Tanaka & Seals, 2008; Visser, 2021). Considering the higher energy expenditure, risk of severe muscle damage (Del Coso et al., 2013, 2017) and gradual decline in performance associated with advancing age (Tanaka & Seals, 2008; Visser, 2021), it is advisable to participate in marathons less frequently compared to shorter races. Each marathon experience brings unique sensations compared to training sessions, highlighting the potential for older runners to confront their declining capabilities with each participation. Consequently, older runners may face increased challenges in planning their race PS.

During both races, for both sexes and all age groups decrease in running speed (positive PS) is observed, with an ES, which was more pronounced in the half-marathon than in the marathon for both sexes (Tables 6–9). Each segment was slower than the previous one, with the exception of the fifth segment. The results of positive PS in all participants are consistent with other studies that examined PSs in age groups between half-marathon and marathon runners in the Vienna (Cuk et al., 2019) and Ljubljana events (Nikolaidis et al., 2019). The fastest ES was observed in younger half-marathon runners of both sexes in comparison to older age groups and marathon runners, which is also in line with the study of Cuk et al. (2019). The lowest ES was noticed in middle-to-old-aged male marathon runners (Table 9). The results of our study indicating an ES in marathoners are consistent with the study of Nikolaidis et al. (2019) while being inconsistent with the same study in half-marathoners, who did not exhibit an ES. The reason for this inconsistency may be attributed to the significantly different sample of participants used in our study for the half-marathon. We actually analyzed a significantly higher number of participants in this discipline (N = 150232 vs. N = 7258). The larger sample size, as noted by some authors (Reusser et al., 2021; Stojiljković et al., 2022), tends to decrease the average result, indicating a higher proportion of recreational runners and beginners. To be specific, it may lead to an increased presence of slower runners who lack experience in planning their PS (Foster et al., 2023), resulting in a larger reserve during the race and potentially expressing an ES, as previously discussed (Koning et al., 2011; Skorski & Abbiss, 2017). Additionally, in the study examined results from Ljubljana (Nikolaidis et al., 2019), the half-marathon was not completely incorporated into the marathon track, which could be a cause to this results discrepancy.

Intriguingly, the results of average race speed in each age group indicate that a lot of them were faster in the marathon than in the half-marathon. Three middle-aged groups of male runners (30–39, 40–49 and 50–59) were faster in marathon than in half-marathon, while in female runners, all of them except the oldest one (≥70). The explanation of faster results in longer races might be found for the same reason as we presume in the previous chapter and consistent with the study of Yang et al. (2022). Moreover, in both sexes, the fastest was 30–39 age group of marathoners (men 11.29km/h and women 10.20km/h, respectively) and the slowest one was in the ≥70 groups of marathoners in both sexes (men 8.82km/h and women 8.20km/h, respectively). These are noteworthy results, as there is evidence suggesting that the decline in performance rate is more significant in individuals above the age of 50 in the marathon compared to shorter distances (De Leeuw, Meerhoff & Knobbe, 2018). Therefore, the findings of the oldest age groups performing slower in longer races compared to shorter races could be attributed to these observations. The faster average race speed observed in middle-age groups of men and most women's groups in longer distances compared to shorter distances may be attributed to the larger number of participants in the half-marathon compared to the marathon. We can therefore assume that in contrast to the marathon sample, a higher proportion of half-marathon participants were recreational runners and beginners. However, despite the larger number of participants, slower average race speeds were observed in the marathon compared to the half-marathon in the oldest age groups of both sexes, which is consistent with the findings of De Leeuw, Meerhoff and Knobbe (2018).

In the study conducted by Nikolaidis et al. (2019), some differences were observed compared to our results. Their findings indicated that the youngest age group (up to 25) was the fastest in both races. Additionally, their study corroborated our findings that the oldest age group was the slowest. The faster results observed in the youngest age groups may be attributed to certain characteristics of the Ljubljana marathon sample, which also had a significantly smaller number of participants (N = 9,137) compared to our study.

7.2. Analysis of Pacing Strategies in the Half-Marathon

Research aim 2 was to analyze PS in an overall sample of half-marathon runners. Each segment was significantly slower than the previous one, except in the fifth segment, where a noticeable ES was observed. The effect size of these differences indicates a large practical significance. Regarding these results, we validated Hypothesis 2, according to which the PS of half-marathon runners is positive.

All previous mass participation new methodology studies that examined the PS in half-marathons also investigated the marathon and compared these two races (Cuk, Nikolaidis, & Knechtle, 2019; Cuk et al., 2019; Nikolaidis et al., 2019; Nikolaidis, Ćuk, & Knechtle, 2019). All of these studies found that pacing is positive in half-marathoners. This finding is in line with the result of our study. However, runners in our study showed an ES, which is consistent with the results of studies which examined PS in Vienna events (Cuk, Nikolaidis, & Knechtle, 2019; Cuk et al., 2019), while it was absent in others which examined PS in Ljubljana events (Nikolaidis et al., 2019; Nikolaidis, Ćuk, & Knechtle, 2019). This inconsistency might be attributed to the different running track configurations, which may have contributed to the absence of an ES in runners participating in the Ljubljana events.

The study by Hanley (2015) found a parabolic reverse J-shape PS among elite runners in the World Half-Marathon Championships, indicating an ES. Most runners finished the first 5 km segment relatively quickly, progressively slowed down until around the 20 km mark and showed an ES eventually. Compared to these results, it seems that the overall sample of half-marathon runners in our study showed a PS very similar to elite half-marathon athletes.

7.2.1. Analysis of Pacing Strategies Based on Performance Level

Research aim 2a was to analyze PSs among half-marathon runners based on performance level. Positive PSs with an ES, with a large effect size of segment CS, were observed across all performance groups. A small effect size, almost reaching the threshold for a medium effect, was found for the differences in CS between each segment among all performance groups in male runners. There were no differences observed between some segments among female runners. The study found a large practical significance of the differences between all performance groups in ACS, regardless of sex, indicating that faster runners demonstrated a more consistent PS throughout the race compared to the slower runners. Regarding these results, we partially validated Hypothesis 2a, according to which higher-performance-level runners of both sexes, pace more evenly compared to runners of lower performance levels in the half-marathon. Additionally, male runners had a more consistent PS compared to female runners within most performance groups, but the differences between sexes had minimal practical significance.

Overall, our study indicates that the runners with higher performance levels, irrespective of sex, tend to demonstrate less variability in their pace compared to those with lower performance. These findings align with the results reported by Piacentini et al. (2019), which showed that slower runners in the half-marathon exhibited a more noticeable decline in pace compared to their predicted finishing time, while faster runners maintained a more consistent pace. This suggests that maintaining an even pace is an efficient metabolic strategy for completing a long-distance race, as highlighted by Rapoport (2010) and Foster et al. (2023).

Similar results were found in the study by Hanley (2015), conducted with elite half-marathon runners, which showed the fastest runners of both sexes largely sustained their segment speeds between the fifth km and 15th km, whereas the slower runners experienced a decrease in speed from the 5 km mark onward. In addition, all runners exhibited an ES. We noticed that slower elite runners in this study showed the same PS as in our sample across all performance groups. However, Hanley's (2015) study was conducted as observational research aimed at describing pacing profiles using average segment speeds as a basis. None of the variables that would describe the magnitude of speed change during the race were utilized, so we don't know the difference in this magnitude compared to our results. In the men's category, the medalist showcased a slightly higher speed during the second and third segments, surpassing their performance in the initial segment. Conversely, among female runners, a slight decrease in speed was evident until the ES. Other authors have reported a similar proportion of high-performance runners with slightly negative PS, while other runners of similar performance levels have demonstrated a positive PS (De Leeuw, Meerhoff & Knobbe, 2018).

The decreased speeds of certain runners between the 15th and 20th km marks observed in the study by Hanley (2015) could either be attributed to fatigue or seen as a strategic tactic for a faster finish, benefiting medal winners, particularly since this group exhibited the fastest ES. Furthermore, the same study noticed that runners who had run in a group during the race experienced a lesser decrease in pace. Running alongside others can result in a smaller decline in pace after the fifth kilometer, but athletes need to exercise caution and avoid joining a group that maintains a pace that is too fast for them.

The finding that faster runners pace more evenly than slower runners was also observed in the study conducted by the first author of the present thesis (Ristanović et al., 2023). As previously mentioned, this study was conducted with a very similar sample size, so this consistency was expected.

In Figure 10, we observed a slightly larger drop in CS from the first to the second segment in the HL group of male runners compared to the MHL group of male, while all higher performance level groups in female runners demonstrated less speed variability than slower ones, between each segment. After the second segment, the HL group of male runners maintained a slightly more consistent pace until the third segment, where the speed was the closest to the average race speed. This less pronounced drop in CS in the male faster group may be attributed to a more rapid start aimed at securing a better position and avoiding the large crowd of runners that is always present at mass races. A faster start is very common and related to better performance outcomes in 5 km races (Filipas et al., 2021; Girard et al., 2013; Menting et al., 2021). Due to the supralinear increase in carbohydrate utilization during metabolic processes with higher running intensity (Romijn et al., 1993), a rapid start can result in greater depletion of glycogen stores, potentially leading to reduced intensity later in the race (Abbiss & Laursen, 2008). Although this more energetic initial phase probably cannot physiologically improve performances in the races of half-marathon duration, securing a better initial position in this case translates to easier maintenance of speed with fewer external distractions when overtaking slower runners. However, we assume that the HL performance group might have more running experience in these races and better warm-up routines prior to starting, which could account for their properly beginning a race in any given conditions (Alves et al., 2023). Furthermore, certain data suggest that athletes with a short fast-start pattern can improve performance by adopting a more evenly distributed PS (Foster et al., 2023; Losnegard et al., 2022). These findings align with our observations.

Our findings revealed a positive PS characterized by a rapid initial phase observed across all performance groups in both sexes. Particularly, we observed a significantly accelerated start in runners with lower performance levels, which was accompanied by subsequent greater decreases in speed. This observation aligns with the findings reported in the study conducted by Deaner et al. (2015). The variations in pacing throughout the race stem primarily from a fast start influenced by higher self-esteem, leading to an overestimation of one's capabilities (Breen et al., 2018). Since our bodies need time to adapt to training stimuli and gradually improve performance (Granata et al., 2018), it is reasonable to assume that a larger proportion of slower runners were beginners with less running experience. These individuals may lack a pacing template and struggle with pacing control, leading to frequent changes in pace and quick fatigue (Deaner et al., 2015; Swain et al., 2020). Key factors for an effective PS include awareness of the endpoint and duration of the race, an internal clock and the ability to recall past PSs (St Clair Gibson et al., 2006). Runners often start races with excessive speed for several reasons. One reason is that they tend to follow the lead pace without considering their abilities or predicted finishing time, as noted by Hanley (2014) and Thiel et al. (2012). Additionally, athletes may increase their pace at the start due to a lower RPE than anticipated, which could be attributed to either their lack of fatigue or the heightened excitement of the race (Koning et al., 2011; Renfree et al., 2014). An assumption of ours regarding the matter is that athletes may feel uncertainty about their performance on a specific occasion and therefore choose to strive for the best possible outcome (Breen et al., 2018).

Another significant factor that can negatively impact PS and performance in long-distance races is climatic conditions, including even minor increases in the outside temperature (Knechtle et al., 2019; Trubee et al., 2014). In the Vienna races, as well as in most other long-distance events, slower runners always finish the race in warmer parts of the day than faster runners. Additionally, slower runners and those with less experience may have limited knowledge about proper hydration practices and their importance (Namineni et al., 2021). Taking into account these findings, the decline in pace observed among slower runners in our study may be attributed to the combination of increased outside temperature and inadequate hydration.

The findings of our study indicated the presence of ES in all performance groups. Slower runners exhibited a more pronounced ES compared to faster runners, coupled with the smaller variations in speed between segments. The noticeable ES reflects the runners' increased caution and management of energy reserves during the race, preventing them from experiencing complete exhaustion before the finish (Koning et al., 2011). This reserve also provides them with extra energy for the ES, which is commonly observed in half-marathon runners (Cuk, Nikolaidis, & Knechtle, 2019; Cuk et al., 2019; Hanley, 2015). This happens when runners become aware of the proximity of the finish line and the decreased risk of not completing the race. This awareness serves as a motivation for them to tap into their remaining energy reserves (Skorski & Abbiss, 2017). It can be argued that this is an ineffective utilization of kinetic energy which could have been utilized more efficiently to establish a faster pace earlier in the race, resulting in a better overall outcome (Foster et al., 2023).

This information is valuable for coaches and professionals working with runners, particularly recreational and beginner runners, to educate them about optimal pacing strategies. In addition to improving performance, it is important to avoid sudden bursts of speed to minimize the risk of health emergencies (Predel, 2014). For example, postural hypotension-induced collapse, though rare, can be associated with life-threatening conditions such as cardiac disorders, heat stroke, cerebral events and hyponatremia (St Clair Gibson et al., 2013). Runners often attempt to push through and cross the finish line too vigorously, leading to disrupted movement dynamics known as “Foster collapse positions” (ibid.). Furthermore, race organizers and official race medical services can benefit from these findings by raising awareness about negative implications of rapid speed changes in long-distance races (Morton et al., 2023), which could help prevent potential health emergencies.

As previously mentioned, the pacing profile in long-distance running is influenced by physiological processes controlled by anticipation and changes in muscle activation (Foster et al., 2023; Koning et al., 2011), which means that years of running experience and previous race participation directly affect race pace. Therefore, more experienced runners are expected to exhibit higher performance levels due to physiological adaptations over time (Granata et al., 2018). As a result, they tend to maintain a consistent pace, while less experienced runners often experience a more noticeable decline in pace (Deaner et al., 2015), which is supported by the findings in our research.

7.2.2. Analysis of Pacing Strategies Based on Sex

The research aim 2b was to analyze PSs among half-marathon runners based on sex. A positive PS with an ES was observed in both sexes. A significant influence of segment CS was found, with a large effect size and discernible differences between each segment. Contrary to our expectations, it was observed that female runners showed a slightly larger CS within most of the segments compared to male runners, but with negligible practical significance of the differences. Moreover, females exhibited a higher ES compared to male runners. Male runners exhibited a more consistent PS throughout the race compared to females. This was also observed in ACS differences between male and female runners, presented in Figure 6. Based on these results, we rejected Hypothesis 2b that female runners pace more evenly compared to male runners in the half-marathon.

A positive PS with an ES in both sexes was also reported in a study conducted by Stanković et al. (2019). The fastest 50 male finishers of the Vienna Half-Marathon exhibited a significant decrease in pace after the first segment. In contrast, the fastest 50 female finishers demonstrated a better and more even pace. The difference in pace between the sexes was significant only in the third segment, where female runners ran relatively faster than male runners. Subsequently, there was a sharp decrease in running pace starting from the fourth segment. Both sexes showed a decline in pace as the race progressed, without an ES. The absence of an ES among elite half-marathoners may be attributed to their giving their best throughout the race without preserving energy for a final speed acceleration (Foster et al., 2023). Variations were observed among the world’s top runners (Hanley, 2015). Male medalists progressively accelerated their pace until the 10th km, maintained it until the 15th km and exhibited a slight decline in pace thereafter until the 20th km. Slower athletes gradually decelerated between the 5 km and the 20 km mark (ibid.). The medalists exhibited the most pronounced ES, although it was evident across all groups, possibly due to slower speeds in the previous 5 km segment. Elite female runners exhibited a slight positive PS with an ES (ibid.). Since the sole purpose of Hanley’s study was to describe the PSs in top athletes at the global level, it did not calculate the results of speed changes throughout the race. It is therefore difficult to compare the segment CS with the findings in our study.

Our study showed significant differences between each segment’s CS in both sexes. This finding is consistent with other studies that have examined similar topics using large participant samples (Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis, Ćuk, & Knechtle, 2019) and a study examining elite half-marathoners (Stanković et al., 2019). Our results showed that runners of both sexes exhibited a decrease in speed variability up to the fourth segment, followed by an increase in the fourth and fifth segments. In the study by Cuk, Nikolaidis and Knechtle (2019), a decrease in speed variability was found up to the fourth segment, followed by an increase in the fourth segment, but then a slight decrease in the fifth segment, indicating an ES. Our study also showed an ES, but with much larger CS values (men 5.74% and women 7.14%) compared to the study by Cuk, Nikolaidis and Knechtle (2019) (men –2.51% and women –1.85%). In our study, these values indicated a much higher ES speed compared to the average race speed, while the study by Cuk, Nikolaidis and Knechtle (2019) showed a speed lower than the average race speed. Since their study involved runners from the same event as our study, albeit limited to a single year (2017), and the running track being the same, the differences between the two studies may be attributed to specific external conditions. The only information we have about the external conditions during the 2017 race is the temperature (*Vienna City Marathon*, 2021). It was at its lowest at 9 am (7.8 °C) and nearly the lowest at 2 pm (11.8 °C) compared to the other 16 years (the highest and lowest temperatures are given in the methods section). Additionally, humidity level or wind speed and direction on the race day could have a significant impact on speed changes in the fifth segment. However, information about these values was not provided on the official race website (*Vienna City Marathon*, 2023). In any case, some official videos from the race day displayed visible indications of the wind's presence (video from the race day in 2017, https://www.youtube.com/watch?v=ezfRkXOSkcc).

Regarding the segment CS results under comparable circumstances, the study by Nikolaidis, Ćuk and Knechtle (2019) showed some different findings. In the 2017 Ljubljana half-marathon, runners exhibited a decrease in speed variability up to the second segment, followed by a negative increase in the third, fourth, and fifth segments in both sexes. These findings differed from both the study by Cuk, Nikolaidis and Knechtle (2019) and our study. The Ljubljana half-marathoners showed a consistent decrease in speed throughout the race, with slightly larger changes in female runners compared to male runners in the first three segments, and smaller changes in the fourth and fifth segments. The comparison between sexes corroborates the findings in our study up to the fourth segment. However, in the fifth segment, female runners in our study once again displayed greater variability in speed.

As seen in Figure 13, male and female runners exhibited very similar speed variability throughout the race, with significant differences observed within each segment. However, these differences were of little practical significance. Similar findings were reported in other studies that explored sex differences in pacing variation among half-marathoners (Cuk, Nikolaidis, & Knechtle, 2019; Nikolaidis, Ćuk, & Knechtle, 2019; Stanković et al., 2019). Female runners demonstrated higher CS than male runners in every segment, except for the second one (1.34% vs. 1.52%, respectively). Likewise, the study conducted by Nikolaidis et al. (2019) identified lower CS in the second segment among female runners (2.26% vs. 2.42%). The smaller CS among female runners can be attributed to the fact that they decelerated more towards the second segment Additionally, a lower CS in female runners was observed in the fifth segment (–4.65% vs. –5.78%) as well, but all differences were of little practical significance (Nikolaidis, Ćuk, & Knechtle, 2019). The same study found no significant differences between sexes in the fourth segment. In contrast to our study, Cuk, Nikolaidis and Knechtle (2019) found that female runners had higher CS than male runners in the first and second segments, but this difference was not observed in the third (0.20% vs. 0.58%) and the fifth segments (–1.85% vs. –2.51%). Furthermore, no significant difference was observed in the second segment. However, similar to our study, all differences were of small practical significance.

The variations in segment CS results between sexes, as observed in both the study by Cuk, Nikolaidis and Knechtle (2019) and our own study, could potentially be attributed to the presence of wind blowing in specific directions (Gray et al., 2023) during the year 2017 when the measurements were taken. Since female individuals biologically have lower levels of strength compared to male individuals (Nuzzo, 2023), they may face greater challenges in resisting frontal and side wind while running. Consequently, male runners may experience fewer difficulties in maintaining their speed during specific segments of the race.

The results indicating a higher segment CS in female half-marathoners compared to male half-marathoners may be attributed to the notable rise in the participation of women in running events, particularly in the shorter distances (Nikolaidis et al., 2021). This implies that the participant samples in these studies may have consisted of a larger percentage of beginner and recreational female runners in comparison to men. Considering that pacing is closely related to previous running experience (Foster et al., 2023; Skorski & Abbiss, 2017; St Clair Gibson et al., 2006), the lower level of experience among the participants could be one of the reasons for greater speed variability in female runners compared to male runners.

We observed that the slope of each segment's CS line was higher in female runners than in male runners, except for the third to fourth segment, where male runners had a slightly higher slope. Specifically, female runners showed a slightly smaller change in speed variability from the third to the fourth segment compared to male runners. This finding is consistent with the results of the studies by Cuk, Nikolaidis and Knechtle (2019) and Nikolaidis, Ćuk and Knechtle (2019) conducted with runners in Vienna and Ljubljana half-marathons held in 2017. Actually, in the study by Cuk, Nikolaidis and Knechtle (2019) female runners exhibited a bigger speed variability between each segment, except between the third and the fourth one, which was shown in our study as well. However, in the study by Nikolaidis, Ćuk and Knechtle (2019) female runners also exhibited less change in speed variability from the fourth to the fifth segment, which differs from our results. Therefore, the results for the fifth segment indicate two situations: higher positive speed variability in female runners compared to male runners (suggesting higher ES), as observed in our study and the study by Cuk, Nikolaidis and Knechtle (2019), while the study by Nikolaidis, Ćuk and Knechtle (2019) revealed less negative speed variability in female runners compared to male runners (indicating reduced speed deceleration). If we consider the assumption that the differences in the fifth segment's CS between Vienna and Ljubljana half-marathoners were attributed to external factors, such as different running track configurations, outside temperature or wind speed and direction, then we can observe that internal factors demonstrate a very similar principle of pace control.

The aforementioned situations could potentially be attributed to psychological factors unique to female runners in comparison to male runners, indicating that women exercise slightly greater caution from the middle of the race and conserve energy for the final segment (Allen & Dechow, 2023; Dechow & Allen, 2023). When approaching the finish line, there is a decrease in the perceived risk of not completing the race and experiencing excessive fatigue (Skorski & Abbiss, 2017). This, in turn, motivates runners to exert their maximum effort (ibid.). Moreover, there is evidence from experienced runners suggesting that women tend to run with higher relative intensity during self-paced treadmill running compared to men (Hanson & Buckworth, 2016), which aligns with our observation of female runners having faster race starts and finishes. Certain findings revealed that male runners exhibited higher levels of overconfidence (Hubble & Zhao, 2016) and competitiveness, indicating a greater tendency to push themselves to achieve the best possible race results (Allen & Dechow, 2023; Dechow & Allen, 2023). As a result, it may be that male runners maintained a higher level of effort throughout the middle part of the race, unlike female runners who conserved more energy. Consequently, male runners had slightly lower ESs due to a lower level of energy reserves.

Another factor that may contribute to the differences in PS between sexes is their physiology. Despite the reduction in the absolute performance gap over time, male individuals will always have a biological advantage (Hallam & Amorim, 2022). Due to lower oxygen-carrying capacity and higher body fat percentage, female runners generally have lower absolute aerobic capacity compared to male runners (Besson et al., 2022). Since aerobic capacity plays a role in helping runners withstand accumulated fatigue during a marathon race (Nikolaidis & Knechtle, 2018b), female runners may experience more difficulty in resisting fatigue, resulting in slightly poorer PS.

Given the substantial influence of pronounced ESs, particularly among female runners, it is suggested to sports and medical experts to provide education to half-marathon participants regarding optimal PSs. This guidance will help them make informed decisions about what is advisable and what may not be recommended. The aim should be to enhance their performance while minimizing the risk of cardiovascular, neural, or other systemic emergencies (Predel, 2014; St Clair Gibson et al., 2013). The educational guidance should emphasize to runners that a sudden surge in speed in the final stage of the race can result in the wastage of their kinetic energy. They should be aware that distributing that energy more effectively through earlier race segments can improve race times (Foster et al., 2023). Finally, by raising awareness among race organizers and medical personnel regarding the risks associated with poor PS and significant speed variability, it becomes feasible to proactively prevent such accidents from occuring (Morton et al., 2023).

7.2.3. Analysis of Pacing Strategies Based on Age

Research aim 2c was to analyze PS among half-marathon runners based on age. Our study found a positive PS with an ES across all age groups and both sexes during the half-marathon races. The youngest age group showed the most pronounced ES in both sexes, with female runners showing a more pronounced effect. Significant influences of segment CS were found in both sexes, although their practical significance was small. The differences between each segment CS were observed within almost all age groups, except for the two oldest groups in both sexes. Furthermore, a significant influence of age group on CS_{1-5} was identified, although the practical significance was negligible. Differences were observed between most age groups within each segment. The results indicated that both sex and age group had a significant influence on the ACS, although the practical significance of sex was negligible and almost reached the threshold for a small effect for the age group. Female runners exhibited higher speed variability throughout the race compared to male runners across ages of 40–69. However, within the age group of 30–39, the situation was reversed, indicating a slight increase in speed variations among male runners. Notably, middle-to-quite-older-aged male runners (aged 40–59) and middle-aged female runners (aged 40–49) exhibited a more consistent pace compared to both younger and older age groups. Taking all of these results into account, our findings provide partial support for Hypothesis 2c, suggesting that middle-aged runners of both sexes pace more evenly compared to younger and older runners in the half-marathon.

In previous studies on a similar topic, younger runners were included in the age groups classified as the oldest (≥60, ≥54). (Cuk et al., 2019; Nikolaidis et al., 2019). These studies used the pace range variable to describe the magnitude of speed changes throughout the race. Our study aligns with the results of Nikolaidis et al. (2019), which showed significant differences between age groups among female runners in the half-marathon, albeit with minimal practical significance. The oldest and youngest age groups demonstrated the highest pace range, while middle-aged female runners (aged 30–49) displayed the lowest pace range, which is consistent with our own findings. Among male runners, a substantial influence of age group on speed variability was observed. Nevertheless, post-hoc comparisons failed to identify any significant differences between each specific age group (Nikolaidis et al., 2019). In the study by Cuk et al. (2019), no significant difference in speed variability across age groups was observed among female runners. However, male runners younger than 25 demonstrated higher speed variability compared to all age groups from 30–54, which was partially in line with our results, suggesting that middle-aged male runners exhibit a more even PS than younger or older individuals. These slightly differing results may be attributed to the significantly smaller sample size in their study compared to ours.

Considering their younger age, it can be inferred that younger runners typically possess less experience compared to middle-aged and older individuals, particularly in long-distance running. This lack of running experience may contribute to less consistent PS (Deaner et al., 2015). However, physiological changes associated with aging may result in less consistent PS among older runners when compared to middle-aged individuals (dos Anjos Souza et al., 2023; Nikolaidis & Knechtle, 2019; Tanaka & Seals, 2008; Visser, 2021). This will be further explained at the end of this section.

The highest number of runners was in the 30–39 age group of male and female runners (N = 29,519 and N = 14,985, respectively), while the lowest was noticed in the oldest groups (N = 600 and N = 97). The lack of significant results in the oldest age groups compared to the other age groups can be primarily attributed to the difference in participant numbers. Due to the significantly lower number of participants in the oldest groups (especially ≥70), certain differences previously observed in the younger groups do not reach statistical significance here.

All age groups of runners initially decreased in speed variability up to the fourth segment but then showed an increase in the fourth and fifth segments. When it comes to male runners, the youngest age group showed the most pronounced ES, which decreased as the age group got older (from CS 7.75% to CS 3.13%). However, some authors have calculated the ES as a percentage difference from the average speed in the fourth segment (Cuk et al., 2019; Nikolaidis et al., 2019). To examine the ES more accurately and compare it with other studies, we applied the same calculation method. Among male runners, the youngest group showed the fastest ES of 10.82%, which decreased as the age groups got older, reaching 8.83% in the oldest group. The order of ES values mostly aligns with a study by Cuk et al. (2019), where the highest ES reached 3.30%, while the lowest was 0.56%. However, there was a deviation from this sequence, as the group aged 50–59 exhibited a higher ES (1.2%) compared to the younger group aged 40–49, which had an ES of 1.11%. Notably, there were significant differences in the ES percentage values between our results and those of their study. Only 30% of half-marathoners exhibited an ES in the study conducted by Nikolaidis et al. (2019). A similar order was found, from highest to lowest values, although the values were very similar from the age of 35 and older (Nikolaidis et al., 2019). It is important to note that the oldest group in their study consisted of individuals older than 54, while in the study by Cuk et al. (2019), it was 60 and older, so we could not observe any further differences in this age range. The differences between our results and these studies may be attributed to the larger number of participants included in our analysis, spanning a sequence of 17 years, while their studies included data from a single event in 2017. Additionally, the different configurations of the running tracks in the Ljubljana and Vienna Marathons could have influenced pace variability in specific age groups, considering the morpho-physiological changes that occur in runners with age (dos Anjos Souza et al., 2023; Nikolaidis & Knechtle, 2019; Tanaka & Seals, 2008; Visser, 2021). These changes are described in the following text.

A similar order was observed among female runners in our study, calculated in the same manner as for male runners. The most pronounced ES, of 11.63%, was observed in the youngest group and it gradually decreased as the age increased, reaching 9% in the oldest runners. When comparing compatible age decades with our study, the same pattern was observed in the study conducted by Cuk et al. (2019), which showed the highest ES of 3.83% and the lowest of 0.41%. There were, however, significant differences in the ES percentage values between our results and theirs. In the study by Nikolaidis et al. (2019), a small number of runners showed an ES in the half-marathon, the larger proportion of runners exhibiting an ES being women, compared to men (34% vs. 27%, respectively). When compared to our study, a similar pattern of ES values among female runners was found in the study conducted by Nikolaidis et al. (2019), although there was a higher ES in the age group of 50–54 compared to the age group of 45–49. However, the oldest group showed a lower ES compared to the 45–49 age group. Since the oldest group in their study consisted of individuals older than 54, while in the study by Cuk et al. (2019), it was age ≥60, we could not observe any further differences in this age range. The same explanation for the differences observed between these studies and ours applies to female runners as well, as mentioned for male runners.

The fifth segment showed a high number of significant differences in CS between age groups in both sexes. Specifically, among runners aged 18–39, a significant difference in CS of ESs was found compared to all other age groups in both sexes. Comparable findings are evident in the 40–49 age group compared to all other groups, except with the oldest one, where no differences were observed. Male runners aged 50–59 demonstrated significant differences compared to all age groups up to the age of 49, while female runners displayed similar differences up to age of 69. In addition, the oldest group in both sexes had a significant difference in CS compared to runners aged 18–39. In the study by Cuk et al. (2019), certain differences were found that partially align with our results. They observed that males aged 25–29 had a significantly higher ES compared to all runners older than 35, which is consistent with our findings. Additionally, in their study, male runners aged 30–34 had a significantly higher ES compared to runners aged 45–49 and those older than 60, which also aligns with our results. Similar results were observed in female runners, where age groups up to 29 demonstrated a significantly higher ES compared to runners older than 35. The age group of 30–34 showed a significantly higher ES compared to runners older than 45. Finally, all runners older than

60 exhibited a significantly lower ES than those aged 35–49. However, due to the age range limitation in their study, where the oldest group consisted of individuals older than 60, we could not observe any further differences in that specific age range. Furthermore, the absence of significant differences between a greater number of age groups in the study by Cuk et al. (2019) can be attributed to the utilization of smaller age ranges, which allowed for more specific findings. The larger number of participants in our study may also have influenced the presence of the differences.

Younger half-marathon runners, both male and female, demonstrated the most pronounced ESs compared to older runners. These findings support our observation of greater speed variability throughout the race among younger runners. However, it is important to note that an ES can occur in long-distance races as runners become aware of the proximity of the finish line and a decrease in the perceived risk of not completing the race. This awareness motivates them to tap into their last reserves of energy (Emanuel, 2019; Skorski & Abbiss, 2017). However, during intense endurance running, there is a potential for cardiac damage and an elevated risk of developing atrial fibrillation (Predel, 2014). Fortunately, it has been observed that cardiac biomarkers and functional changes can normalize very quickly (ibid.). This phenomenon was interpreted as a response of the heart muscle to strenuous exercise, known as “cardiac fatigue” (ibid.). Our data can be valuable for sports and medical professionals in educating young long-distance runners on optimal PSs, aiming to enhance their performance while reducing the risk of health implications associated with rapid speed changes (Predel, 2014; St Clair Gibson et al., 2013). Additionally, race organizers and official race medical services can benefit from these findings by raising awareness about the negative consequences of extremely intense ESs and speed changes in long-distance races, thereby preventing potential medical consequences (Morton et al., 2023).

The fastest male half-marathon runners were the age group of 18–29 (11.07 km/h), followed closely by the 30–39 age group at nearly identical average speed (11.06 km/h). As the age groups got older, the runners became slower, with the slowest group being ≥70 (8.99 km/h). Similar results were observed in the study conducted by Nikolaidis et al. (2019), where the youngest group up to the age of 25, showed the fastest average speed (11.7 km/h), while the oldest group, aged over 54, was the slowest (10.76 km/h). Their study showed faster average speeds compared to ours, particularly in the slowest group. One possible reason could be the significantly lower number of participants, which may have inflated their results (Stojiljković et al., 2022). Another reason could be that the oldest group in their study consisted of much younger runners, who naturally exhibit better performance (Leyk et al., 2007).

In our study, slight differences were observed in female runners, with the fastest group being the 30–39 age group (9.84 km/h), followed by the youngest group (9.75 km/h), while the slowest group was the oldest one (8.35 km/h). Certain differences were shown in the study by Nikolaidis et al. (2019), where the youngest group, up to the age of 25, showed the fastest average speed (10.19 km/h), while the oldest group, aged over 54, was the slowest (9.47 km/h). Their study also showed faster average speeds compared to ours, especially in the slowest group, as was the case with male runners. This could also be attributed to the significantly smaller number of participants, as well as the younger age of the oldest group. The study by Leyk et al. (2007) indicated that there is no significant age-related decrease in performance up to the age of 50 in trained runners of both sexes, which aligns with the results of our study.

Furthermore, our results indicating that female runners reached their best performance at an older age than male runners (30–39 vs. 18–29) are not consistent with the results by Knechtle and Nikolaidis (2018). In their study, the best performance was observed in female runners younger than 35 and the age group of 35–39, while in male runners it was observed in the age group of 35–39. However, their study divided age groups into 5-year intervals, the youngest group including all runners younger than 35. These factors may contribute to the inconsistency of results. Additionally, the number of runners in the youngest male age group in our study was significantly lower than in the 30–39 age group (N = 19,366 vs. N = 29,519), while in female runners, the numbers were very similar (N = 13,159 vs. N

= 14,985). This suggests that the best performance by the youngest group in men may be attributed to the lower number of runners, especially when considering the negligible difference between them and the subsequent older group (0.01 km/h).

When it comes to differences in the average race speed by sex, our study showed the largest difference in the youngest group (11.9%), followed by the 40–49, 30–39, 50–59, and 60–69 age groups. The smallest difference was found in the ≥70 group (7.12%). In the study conducted by Nikolaidis et al. (2019), the largest difference by sex was found in the 25–29 age group (15.7%), while the smallest difference was observed in the 30–34 age group (12.2%). Although the largest difference between sexes was consistent between their study and ours, the smallest difference did not align. However, in the 30–39 age group, a smaller difference compared to the older group (aged 40-49) was also observed in our study. Due to the age range limitation in their study, where the oldest group consisted of individuals older than 54, we could not observe any further differences in that particular age range. We can therefore assume that the results of the two studies are generally aligned.

The less consistent PS observed in older runners may be attributed to age-related variations in physiological and training characteristics (Nikolaidis & Knechtle, 2019). VO_2max, lactate threshold, and running economy are key parameters in determining endurance performance, but they typically decline with age (Lee et al., 2019; Tanaka & Seals, 2008), although running economy stays relatively stable in trained adults until around the age of 60 (dos Anjos Souza et al., 2023). The main factor influencing performance decline appears to be a decrease in VO_2max, estimated at around 10% per decade, influenced by both central and peripheral changes such as reductions in maximal stroke volume, maximal heart rate, and arteriovenous oxygen difference (Hawkins & Wiswell, 2003; Tanaka & Seals, 2008). Morphological changes, including reductions in lean body mass, infiltration of fat into muscles, and alterations in fiber type composition (specifically, an increase in the percentage of type I fibers), can also impact performance (Maharam et al., 1999; Visser, 2021). Age-related muscle atrophy, typically noticeable around the age of 50, may further affect older runners (Faulkner et al., 2008). Studies indicate an annual loss of skeletal muscle mass ranging from approximately 0.26% to 0.56% in individuals aged up to 70 years old (Visser, 2021). Consequently, aging is associated with declining endurance exercise performance, primarily influenced by a reduction in the intensity and volume of exercise that can be sustained during training sessions (Nikolaidis & Knechtle, 2019). As a result, older runners may encounter challenges in maintaining the same training volume and intensity as they age.

Increasing outside temperature impacts differently on runners of different ages, with a higher negative impact on male runners aged 30–64 and female runners aged 40–64 (Weiss et al., 2022). Since older runners normally run slower than younger ones, due to the previously mentioned physiological and morphological changes that occur with age (dos Anjos Souza et al., 2023; Nikolaidis & Knechtle, 2019; Tanaka & Seals, 2008; Visser, 2021), they spend more time running the same distance. Therefore, increased outside temperature during the race might have a higher impact on their speed and overall PS.

7.3. Analysis of Pacing Strategies in Marathon

Research aim 3 was to analyze PS in an overall sample of marathon runners. A large practical significance was observed in the differences between the mean speeds of each segment. All marathoners exhibit a decrease in speed up to the fifth segment, followed by an increase in the fifth segment, indicating a prominent ES. Based on these results, we validated Hypothesis 3, according to which the PS of marathon runners is positive.

Positive PS in the marathon was also shown in previous studies (Cuk et al., 2021; De Leeuw et al., 2018; Hubble & Zhao, 2016; Kais et al., 2019; Stojiljković et al., 2020). Some of the previous mass participation new methodology studies that examined the PS in marathon also examined the half-marathon (Cuk, Nikolaidis, & Knechtle, 2019; Cuk et al., 2019; Nikolaidis et al., 2019; Nikolaidis, Ćuk, & Knechtle, 2019) or 10K race (Cuk et al., 2021) and compared two races. All these studies found that pacing in marathoners is positive, coupled with the characteristic ES, which aligns with the results of our study.

7.3.1. Analysis of Pacing Strategies Based on Performance Level

Research aim 3a was to analyze PSs among marathon runners based on performance level. Our findings revealed that almost all performance groups in both sexes demonstrated a positive PS characterized by an ES. However, male runners in the HL performance group showed an absence of ES. The influence of segment CS was found to be substantial, with a large practical significance, indicating differences between each segment CS in both sexes. There was a significant impact of performance group on segment CS, although the practical significance was small, almost reaching the threshold for a medium effect. The influence of performance level on ACS had a medium practical significance. These findings indicate that faster runners exhibited a more even pace throughout the race compared to their slower counterparts. Differences between almost all segment CS were observed among all performance groups in both sexes. Female runners generally showed a more consistent PS within each performance group, although the practical significance of these variations was limited. ACS decreased as the runners' performance level increased in both sexes. Based on these results, we confirmed Hypothesis 3a, according to which higher-performance-level runners of both sexes, pace more evenly compared to runners of lower performance levels in the marathon.

Positive PSs were observed among almost all performance groups and in both sexes, which is consistent with the results of other studies (Cuk et al., 2021; De Leeuw et al., 2018; Hubble & Zhao, 2016; Kais et al., 2019; Nikolaidis & Knechtle, 2019; Stojiljković et al., 2020). Our results also indicate that faster marathoners, irrespective of sex, tend to exhibit less speed changes compared to slower runners, which was also shown in other studies (ibid.). These results are consistent with the findings of a previous study conducted by the first author of this thesis (Ristanović et al., 2023). The study by Ristanović et al. (2023) encompassed a narrow range of years, specifically the Vienna marathon events from 2006 to 2018. In contrast, our study adopted a broader time frame, spanning from 2006 to 2023. Consequently, the sample size of participants was smaller in their study compared to ours (208,760 vs. 233,083). Given the similarity in sample size between the two studies, this consistency was anticipated, as mentioned earlier.

The studies examining high-performance athletes also stated that elite and highly trained marathon runners typically strive to maintain an even pace throughout the race (Muñoz-Pérez et al., 2020). Runners demonstrating a more evenly distributed PS were significantly faster than runners demonstrating a positive PS. In the World Championships and Olympic Games, both male and female medalists predominantly maintained an even pace from the 10th kilometer onwards. Individuals who completed the race at a slightly slower pace tended to fall behind the leading group around the halfway point (Hanley, 2016). Research has also shown that running alongside a group of runners with similar performance levels is more effective than running alone (Hanley, 2015, 2016). Hence, sustaining an even pace appears to be the optimal metabolic strategy for successfully finishing a long-distance race (Rapoport, 2010). Recent research findings suggest that achieving a negative or even PS, along with performing well in a half-marathon completed in the weeks leading up to the marathon and adopting packing behavior, can accurately predict marathon performance (Muñoz-Pérez et al., 2024). When considering age as a factor in this prediction equation, it is crucial to exercise caution (ibid.). The study suggests that implementing a competitive strategy that focuses on maintaining a negative or even pacing pattern during the marathon race can improve overall marathon performance (ibid.).

Our results demonstrated a gradual decrease in speed throughout the race, with speeds falling below the average race speed after the third segment (30th km). These findings partially align with the results of studies by Stojiljković et al. (2020) conducted at the Belgrade Marathon and Santos-Lozano et al. (2014) conducted at the New York Marathon, where this decrease occurred at a faster rate. Their studies showed that slower runners start the race significantly faster than the average race speed for the first 20–25 kilometers. However, they subsequently experience a significant decrease in speed, falling below the average race speed. It is worth noting that in our study, only the female runners LL group exhibited a decrease in speed below the average race speed in the third segment, while the remaining groups exhibited this decrease in subsequent segments. These differences may be attributed to different race configurations because both of them have higher elevation differences than the marathon course in Vienna. The elevation difference in the New York Marathon is 390 m, while we couldn't find any official information on the website of the Belgrade race. However, it is well-known that there is a relatively steep ascent in the final segments there. Our study revealed that the slowest group of runners exhibited a significantly faster start compared to the other groups. This suggests that a greater accumulation of fatigue up to the third segment could be the primary explanation for their more abrupt and earlier decline in speed (Deaner et al., 2015) when compared to faster runners.

The pacing profile in long-distance running is shaped by anticipation-based control of physiological processes, involving muscle activation adjustments (Foster et al., 2023; Koning et al., 2011). It requires time and experience to understand environmental conditions, metabolic functions and fuel reserves for a specific race distance (Foster et al., 2023; St Clair Gibson et al., 2006). Less experienced runners typically exhibit lower performance levels due to physiological adaptations taking time to develop (Granata et al., 2018). The number of years running and past race participation directly influence race pace, regardless of sex, age, or current performance level (Deaner et al., 2015). Experienced runners tend to maintain a consistent pace, while less experienced runners exhibit a more noticeable decline in pace (ibid.), which aligns with the findings of our research.

Most performance groups of runners showed a decrease in speed variability up to the fourth segment, followed by a negative increase in the fourth one, and a decrease in the fifth segment. The only exception was the HL group, where a negative increase in speed variability was observed in the fifth segment as well, indicating the absence of an ES.

Our findings revealed that nearly all performance groups exhibited an ES. It is worth noting that slower runners displayed a more prominent ES in comparison to faster runners, which was coupled with the smaller speed changes between segments. An ES was observed across all female groups, with the lower-performance groups showing more pronounced ones. Only the HL group of male runners did not exhibit ES, while the MHL group exhibited only a slight increase in speed in the fifth segment (0.2 km/h). Similar results were observed in the study by Ristanović et al. (2023), where the absence of an ES was shown in both the HL group and the MHL group of male runners, with the speed remaining constant in the fourth and fifth segments (10.81 km/h). In our study, we observed a slightly lower average speed in the fourth and fifth segments in male marathon runners (10.74 km/h and 10.76 km/h), indicating a higher proportion of slower runners. Therefore, the presence of an ES in the MHL group of male runners in our study, compared to the study by Ristanović et al., (2023) could be attributed to the higher number of participants, which influenced the results (Stojiljković et al., 2022; Vitti et al., 2020). This was evidenced by the differences in average speeds. Slower runners typically exhibit a more pronounced ES due to limited experience and uneven energy distribution, leading to a cautious approach and increased energy utilization towards the end of the race (Deaner et al., 2015; Koning et al., 2011). Given that immediate speed changes and the high-intensity run at the end of a long-distance race might increase the risk of health crises (Morton et al., 2023; Predel, 2014; St Clair Gibson et al., 2013), sports and medical professionals should provide targeted education to slower marathon runners.

Based on the aforementioned pieces of evidence, we assume that the absence of an ES in high-performance runners can be attributed to their superior energy distribution, stemming from accurate self-assessment and the inability to make sudden changes toward the end (Foster et al., 2023). Based on this, we can assume that physiological factors play a more significant role than psychological factors. On the other hand, pacing involves aspects such as anticipation, awareness of the finish line, experience, and sensory feedback (Skorski & Abbiss, 2017). Being aware of the proximity of the finish line can motivate runners to tap into their remaining reserves (ibid.), which highlights the influence of psychological factors rather than physiological ones. In addition, this reserve gives them additional energy for the ES, a phenomenon frequently observed among slower marathon runners (Nikolaidis & Knechtle, 2017). It is interesting to note that men's world records were characterized by an even PS with a strong ES (Muñoz-Pérez et al., 2023). However, the prominent ES observed in athletes at this level is likely influenced by tactical decisions aimed at defeating the strongest opponents (Hanley, 2015).

Our results, which indicate significant differences in ACS between each performance group, are consistent with the study by Stojiljković, Matić and Papić (2020), who examined 937 participants in the 2019 Belgrade Marathon. In that study, a significant difference in PS was observed across the four performance-level groups, with values very similar to what we found in our sample. In the overall sample, ACS values were demonstrated in the following order from the HL to LL group: 3.48%, 4.90%, 6.44% and 7.10%. We also noticed that these values fall within the range observed in our sample for both male and female runners, except for the MLL group, where a higher ACS was found compared to male and female runners in our study (men 5.88% and women 4.65%).

As mentioned earlier in the section that compared PS in the half-marathons and marathons based on performance, long-distance races are affected by climatic conditions and slight increases in outside temperatures, which can negatively impact pace and performance (Knechtle et al., 2019; Trubee et al., 2014). In the Vienna races it is consistently observed that slower runners complete the race during warmer hours in comparison to faster runners. In our study, the fastest race time we analyzed was slightly over two hours (men: 2:05:08, women: 2:20:59 h:min:s), while the slowest participants, both male and female runners, completed the marathon in 6:42 h:min. This indicates a difference of approximately four and a half hours, with the slower runners finishing in the afternoon, around 3–4 pm. The outside temperature in April is significantly higher during these hours than in the morning, so slower runners spend more time running in elevated temperatures than faster runners. Additionally, slower runners and those with less experience may have limited knowledge about the importance of proper hydration practices (Namineni et al., 2021). Therefore, the observed decline in pace among slower runners may be attributed to a combination of increased outside temperature and inadequate hydration.

7.3.2. Analysis of Pacing Strategies Based on Sex

The research aim 3b was to analyze PSs among marathon runners based on sex. A positive PS with an ES was observed in both sexes, with the ES being more pronounced in female runners. A significant influence of segment CS was found, with a medium practical significance. Almost every segment showed significant differences from one another in both sexes. Female runners exhibited smaller CS in each segment compared to male runners, indicating a more consistent PS. However, the differences between sexes had minimal practical significance. Similar findings were also observed in ACS differences between sexes, as presented in Figure 6. Based on these results, we obtained partial validation for Hypothesis 3b, according to which female runners pace more evenly compared to male runners in the marathon.

A positive PS with an ES was also observed in other studies examining PS in marathon races (Breen et al., 2018; Casado et al., 2021; Cuk, Nikolaidis, & Knechtle, 2019; De Leeuw et al., 2018; Nikolaidis, Ćuk, & Knechtle, 2019). Contrasting findings emerged for world record holders demonstrating both, a negative (Díaz et al., 2019) and an even PS with an ES (Muñoz-Pérez et al., 2023).

Previous studies reported similar differences in PS between sexes among non-elite marathon runners, just like our study (Cuk, Nikolaidis, & Knechtle, 2019; Kais et al., 2019; Nikolaidis, Ćuk, & Knechtle, 2019; Stojiljković et al., 2020). However, the study conducted by Nikolaidis, Ćuk and Knechtle (2019) found that male runners had lower CS compared to female runners only in the third race segment. Male runners continued to decrease their speed in subsequent segments. This suggests that there was one segment with a transitional speed that was close to the average race speed. Recreational female runners were found to adopt a more cautious starting pace, maintain a more consistent pace throughout the marathon, and exhibit less speed decline in the final portion of the race (De Leeuw et al., 2018; Hernando et al., 2020; Hubble & Zhao, 2016; March et al., 2011; Stojiljković et al., 2020). The study by Hernando et al. (2020) even revealed that women ran up to 4.5% faster than men in the last kilometers (from the 40^{th} km to the finish line).

The faster start was observed in both sexes, although it was more pronounced in male runners. Such rapid starts in the initial segment of the race can be attributed to factors like “pre-race enthusiasm” or the absence of fatigue at that point (Koning et al., 2011). Consequently, fatigue is more likely to set in later during the race, leading to a decrease in running speed (Deaner et al., 2015), which was also found to be more prominent in male compared to female runners.

Figure 21 shows a larger decrease in speed among male compared to female runners, particularly in the fourth segment, followed by a higher ES in female runners. Similar findings of a larger decrease after the 35 km mark were also observed in other studies (Cuk et al., 2019; Deaner et al., 2015; Muñoz-Pérez et al., 2023). The phenomenon could be attributed to glycogen depletion (Coyle, 2007), rather than psychological factors (Allen & Dechow, 2023; Dechow & Allen, 2023). Male individuals may be more susceptible to glycogen depletion (Impey et al., 2020) and “hitting the wall”, which could explain the greater decrease in speed in the second half of the race compared to female runners (Smyth, 2021). This observation could also be attributed to evidence suggesting that the contrast between sexes becomes more prominent at higher external temperatures (Trubee et al., 2014). Specifically, female runners are more likely to employ effective strategies to reduce the risk of heat-related illnesses during physical exertion (Périard et al., 2017). Since the Vienna marathon races can start as early as 9 am and last for almost 7 hours (*Vienna City Marathon*, 2023), the increased outside temperature may have an impact on the course and outcome of the race.

The ES observed in both sexes, but more pronounced in female runners, reflects caution and energy reserves, preventing exhaustion before the finish line (Koning et al., 2011). The study by Nikolaidis et al. (2019) also demonstrated more female runners showing an ES (84.5%) compared to male runners (67.7%). This burst of speed occurs when runners become aware of the proximity of the finish line and perceive a decreased risk of not completing the race. This realization encourages them to tap into their remaining energy reserves (Skorski & Abbiss, 2017). Sports and medical professionals can play a crucial role in educating female marathon runners, specifically, to optimize PS, thereby enhancing performance and reducing the likelihood of health emergencies (Predel, 2014; St Clair Gibson et al., 2013). By increasing awareness among race organizers and medical services about the risks associated with pronounced ESs and pace variations, critical health events can be prevented (Morton et al., 2023).

It is worth noting that some authors did not find significant differences in PSs among elite runners (Trubee et al., 2014). Even elite female runners with relatively lower performances were observed to start the race at a pace that exceeds their abilities, possibly influenced by the faster athletes they aim to keep up with (Renfree & St Clair Gibson, 2013). Similar patterns were noticed in elite men participating in the World Cross Country Championships (Hanley, 2014). Additionally, the studies showed both negative (Díaz et al., 2019) and even PSs with an ES (Muñoz-Pérez et al., 2023) in men’s world record holders. In contrast, women’s world record holders displayed less consistency in PSs (Díaz et al., 2019) and showed a negative PS with an ES among medal winners (Hanley, 2016).

Regarding the performance level of marathoners, the study by Kais et al. (2019) revealed interesting findings regarding differences in sexes. When comparing male and female runners within the same performance group, it was found that male runners experienced a more significant speed decline. This difference was particularly noticeable in the group with finishing times ranging from 2:15 to 2:30 h:min and across all performance groups finishing the race in between three and six hours (Kais et al., 2019). A significant disparity between sexes was observed in the 25–30 km segment (Nikolaidis & Knechtle, 2018a). In our study, the largest sex difference in CS was noticed in the fifth segment, indicating a higher ES in female runners (Figure 21).

Male runners generally outpace female runners by around 10–20% across various race distances (Knechtle & Nikolaidis, 2022; Nikolaidis et al., 2017), with a noticeable value of 10.7% observed in the Boston Marathon over a significant number of years (1972–2017) (Knechtle et al., 2020). Additionally, this performance gap is even greater among top athletes and medal winners (18.3% and 15.5%, respectively) (ibid.). This discrepancy in performance is primarily attributed to biological differences, particularly in physiology (Nuzzo, 2023, 2024). However, it is worth noting that the gap between the sexes has been decreasing over the years (Knechtle et al., 2020). In our study, the difference in average race speed between male and female runners was 9.2% (10.96 km/h and 9.95 km/h), which is lower than the values mentioned earlier. The average marathon running pace has decreased over the years due to the rising number of participants (Stojiljković et al., 2022), particularly impacting male runners and narrowing the performance gap between the sexes (Lepers & Cattagni, 2012). Moreover, women's participation in races has seen a greater increase compared to men (Lepers & Cattagni, 2012; Stojiljković et al., 2019).

Differences in PS between sexes, with female runners maintaining a more consistent pace compared to male runners, can be attributed to physiological factors. Female individuals have lower susceptibility to fatigue (Hunter, 2014, 2016), possibly due to a higher proportion of type 1 muscle fibers (Nuzzo, 2024) that rely more on fat oxidation, contributing to reduced reliance on carbohydrates and amino acids compared to male individuals (Tarnopolsky, 2008). In contrast, a higher percentage of type 2 muscle fibers in male individuals (Nuzzo, 2023, 2024) leads to greater carbohydrate utilization and potential "hitting the wall" (Impey et al., 2020; Smyth, 2021). Additionally, male runners are especially affected in long races like marathons due to fuel availability challenges beyond two hours of racing (Joyner & Coyle, 2008). Evidence shows that 28% of male runners experience the "hitting the wall" phenomenon during a marathon race, whereas in female runners, this occurrence is observed at a significantly lower rate of 17% (Smyth, 2021). Female individuals also exhibit faster oxygen extraction dynamics during moderate exercise and demonstrate enhanced mitochondrial oxidative function compared to male individuals (Cardinale et al., 2018). Their muscle metabolism has a greater capacity for ATP synthesis through oxidative phosphorylation (Ansdell et al., 2020). Moreover, female individuals are more likely to employ strategies to reduce heat-related risks during physical exertion (Périard et al., 2017). All of these factors provide possible explanations for the evidence that female runners, when they hit the wall, demonstrate a shorter distance of slowing down compared to male runners (9.6 km vs. 10.7 km, respectively) (Smyth, 2021).

Differences in marathon PS between sexes can be attributed to psychological factors as well. In terms of psychological factors between sexes, recent studies (Allen & Dechow, 2023; Dechow & Allen, 2023) showed that female runners approach goal-setting for marathons differently from male runners. Some female runners prioritize completing the race within a broader time range, while others intentionally refrain from setting specific time goals to alleviate the pressure of competition (ibid.). Some may also be unaware of men's emphasis on precise finish time goals as performance metrics (ibid.). Although more female runners adopt an even PS, they are not driven primarily by stringent finish time goals (ibid.). The stringent finish time goals has little to no impact on the running strategy of women (Dechow & Allen, 2023). Female runners clustering around precise finish time goals are less likely to engage in an ES (Allen & Dechow, 2023; Dechow & Allen, 2023). In contrast, male runners clustering around precise finish times tend to maintain a consistent pace, while those employing an optimal strategy increase speed or sprint to achieve their time goal (ibid.). Pre-race planning and setting time goals are particularly beneficial for male runners as it helps counter their inclination to exert excessive effort at the start of the race (Allen & Dechow, 2023). These findings suggest that male runners use precise finish times as benchmarks and aim to avoid the disappointment of falling short of their goals (Allen & Dechow, 2023; Dechow & Allen, 2023). The results of our study demonstrated that both female and male runners exhibited a fast start, but female runners quickly assessed their capabilities and showed a greater decrease in speed in the second segment. This suggests that male runners may tend to overestimate their abilities at the beginning of the race, leading to a significant decline in speed as the race progresses (Hubble & Zhao, 2016). Therefore, overconfidence can be considered as a psychological factor contributing to the less efficient PS observed in male runners (ibid.).

Less pace variability observed in female runners may also be influenced by social factors. According to a recent review study by Proverbio (2021), there are social differences in the level of interest in social stimuli. Women tend to show a greater interest in interacting with other people (ibid.), which can contribute to a more enjoyable running experience as they have the opportunity to spend time with other runners.

7.3.3. Analysis of Pacing Strategies Based on Age

Research aim 3c was to analyze PS among marathon runners based on age. Significant differences were observed between almost every segment CS among all age groups in both sexes. Age group was found to have a significant influence on segment CS as well. The highest ES was noticed in the youngest age group among male runners, while both the oldest and youngest age groups exhibited a higher ES compared to others among female runners. Female runners demonstrated lower ACS and, consequently, a more consistent PS compared to male runners across all age groups up to the age of 69. The significant influence of age group on ACS was demonstrated by the middle-aged runners (30–49 years old) exhibiting a more even PS compared to the younger and older runners in both sexes. However, despite the minimal or trivial practical significance of all these differences, we partially validated Hypothesis 3c, suggesting that middle-aged runners of both sexes pace more evenly compared to younger and older runners in the marathon.

The results of our study indicated a positive PS with an ES in all age groups of both sexes. Furthermore, each segment was slower than the previous one, except for the last segment, indicating an ES. These findings are consistent with previous studies (Cuk et al., 2019; Nikolaidis et al., 2019; Nikolaidis & Knechtle, 2018a, 2019). Previous research has also noted differences in PSs among age groups (Kais et al., 2019; March et al., 2011; Nikolaidis & Knechtle, 2017), which also aligns with our results.

The age group of 40–49 had the highest number of runners, with 23,826 male and 5,537 female runners. Similar findings were reported in other studies (Cuk et al., 2019). These results are not surprising since there has been a significant increase in the participation of both sexes over the age of 40 in marathon events since 1980 (Lepers & Cattagni, 2012). In Serbia, the age group of 30–39 exhibited the highest participation rate in the Belgrade marathon from 2007 to 2019 (Stojiljković et al., 2019). This data can be attributed to factors such as physical requirements, social influences, and the availability of time for individuals within these age ranges (Anthony et al., 2014).

The fastest runners were those aged 30–39, both among males (11.29 km/h) and female runners (10.20 km/h), while the slowest group consisted of the oldest runners. These results align with the data suggesting that peak endurance running performance remains consistent until approximately 35 years of age, after which there are gradual declines until the late 50s, followed by greater decrements (Tanaka & Seals, 2003, 2008). Different results were observed in the study conducted by Nikolaidis et al. (2019). In their study, the youngest group aged up to 25 was the fastest, while runners aged over 54 were the slowest. Since the oldest group in their study consisted of runners older than 54 years of age, the result of the slowest performance aligns with our findings. However, the result of the fastest group does not align with our findings, which may be attributed to the larger number of participants in our study spanning 17 years, compared to their study that focused on a single year. Consequently, the age groups participating in the marathon may have changed over time due to the increasing number of participants (Reusser et al., 2021). Data indicate a noticeable decline in performance (ranging from 1:52 to 3:02 min:s per year) across all age groups up to 50 years old. However, marathoners aged over 50 demonstrated relatively consistent performances during the years. Contrary findings were presented in the study conducted by Stojiljković et al. (2022), which explored running performances of age groups in the Belgrade Marathon from 2007 to 2019. The study found that the fastest group in the overall sample consisted of individuals aged 40–49, while the slowest group comprised participants under the age of 30. However, this study revealed that the age group of 30–39 is the fastest when considering the top 10 finishers in each age group, which aligns with our findings. As expected, the oldest age group of ≥60 naturally had the slowest participants.

The difference in average race speed between sexes in our study was highest among individuals aged 40–49 (10.37%), but decreased in younger and older age groups, reaching 7.3% in the oldest age group. These findings provide partial support for recent studies that observed a gradual reduction in the performance disparity between sexes as individuals enter older age groups (Nikolaidis et al., 2021; Waldvogel et al., 2019; Yang et al., 2022).

The results of our study indicate that middle-aged runners exhibit a more evenly distributed PS compared to both younger and older runners among both sexes. These findings are consistent with other studies on the same topic, where the oldest age group consisted of runners younger than in our study (65 and older, 60 and older, and 54 and older) (Cuk et al., 2021; Cuk et al., 2019; Nikolaidis et al., 2019). Moreover, several studies (Nikolaidis & Knechtle, 2018a, 2019) suggest negligible differences in speed variability through the race among various age groups, which is consistent with our findings. One study observed no significant difference in pace variability across age groups among female runners, whereas male runners younger than 30 and male runners older than 60 demonstrated higher pace variability compared to other age groups (Cuk et al., 2019). These slightly differing results may be attributed to the considerably lower number of participants in our study, particularly among female runners (N = 1276). The study by Nikolaidis and Knechtle (2017) found that younger age groups had greater speed variability during the race compared to older age groups, particularly among slower runners. In their study, they compared runners of different ages but within the same race finish time groups. It is expected that the differences would be smaller when considering the entire sample within an age group, regardless of the final race result. Therefore, if they found significant differences in this analysis, it can be concluded that young people have a less consistent pace.

The study by Kais et al. (2019) categorized participants into two age groups: veterans (runners over 40) and non-veterans (up to 40 years old) who took part in the World Marathon Majors races in 2015. They specifically compared the pace between the first and second half of the race and found that the veterans had a more consistent pace when considering race results and sex. However, it is important to consider narrower ranges of age groups for a more detailed analysis. Therefore, it is crucial to differentiate between different age categories, such as 40-49 and 50 years and older, when referring to older runners. In our study, middle-aged runners were approximately between the ages of 30 and 49 years old, younger runners were under 30, and older runners were 50 years old and above.

All age groups of runners in our study show a decrease in speed variability up to the fourth segment, followed by a negative increase in the fourth segment, and then another decrease in the fifth segment, indicating the presence of an ES. Similar pace at the start was observed in most age groups between sexes. However, female runners showed a slightly higher decrease in the second segment, followed by maintaining a more stable speed in the third segment and showing less decrease in the fourth segment. As a result, female runners conserved more energy for a higher ES compared to male runners. Very similar findings were observed by Nikolaidis and Knechtle (2018a) among age groups of male and female runners in the 2015 New York City Marathon. A higher ES in females was also observed when analyzing 11 years of the New York City Marathon (2006–2016) (Nikolaidis & Knechtle, 2017).

More significant differences between age groups were observed in the first and fourth segments among female runners of our study, while smaller significance was noticed in the other segments (Table 14). This may indicate a tendency for different starting performances among most age groups, followed by a similar stabilization of speed in the second and third segments of the race caused by the accumulation of fatigue (Cuk, Nikolaidis, & Knechtle, 2019; Hanley, 2015). Furthermore, there appear to be varying levels of fatigue resistance between age groups in the fourth segment, with similar final accelerations when the finish line is very close. The challenge of fatigue resistance in older runners may arise due to the morpho-physiological changes that occur with age (Hawkins & Wiswell, 2003; Tanaka & Seals, 2008; Visser, 2021), as will be explained later in this section.

As observed in Figures 22 and 23, the youngest age group among male runners and the oldest and youngest groups among female runners, demonstrated the most pronounced ES compared to other age groups. The findings regarding the most pronounced ES in male runners align with the study by Cuk et al. (2019), where the percentage faster or slower than the average speed in the fourth segment was used. When calculated in the same manner, the results of our study, as presented in Table 7, revealed that among male runners, the highest ES of 2.77% was observed in the youngest group. This was followed by the oldest group and runners aged 60-69, 30-39, and 50-59 (with ES values of 1.11%, 1.1%, 1%, and 0.81% respectively). The smallest ES of 0.5% was observed in the 40-49 age group. Table 9, shows quite different results in female runners, with the highest ES in the oldest group (3.91%). This was followed by the youngest group (3.62%) and runners aged 30–39, 50–59, 40–49 and 60–69 (2.9%, 2.5%, 2.48% and 2.34%, respectively). A much higher ES was observed in female runners compared to males across all age groups, which aligns with the study by Nikolaidis et al. (2019). Greater stability in pace and reduced decline observed in recreational female runners during the marathon can be attributed to their characteristic approach (De Leeuw et al., 2018; Hernando et al., 2020; Hubble & Zhao, 2016; March et al., 2011; Stojiljković et al., 2020). This suggests that females exercise more caution and conserve energy during the race, which provides them additional energy for the ES (Koning et al., 2011). In the study conducted by Hernando et al. (2020), it was discovered that female runners exhibited a speed advantage of up to 4.5% over male runners during the final kilometers, specifically from the 40th km to the finish line. This finding further confirms the previously mentioned observations.

Since we analyzed age decades in our study, we calculated average values for compatible decades based on the results of the Cuk et al. (2019) study. In their study, the youngest group among male runners showed the most pronounced ES (2.04%). This was followed by the runners aged 30–39 (0.82%), 50–59 (0.75%), 40–49 (0.38%), and the lowest value, shown in the oldest group, aged ≥60 (0.31%). Among female runners, the most pronounced ES was observed in the youngest group (2.73%). This was followed by the group aged 40–49 (2.67%), 30–39 (2.62%), 50–59 (1.99%), and the lowest value, in the oldest group aged ≥60 (1.88%). When we combined the findings from the two oldest female groups in our study to create a single age category of 60 and above, with the intention of comparing these outcomes to the results in the same age category in the study conducted by Cuk et al. (2019), we also observed the highest ES in the youngest group. Therefore, the results showing the highest ES in the youngest age groups in both sexes from the study by Cuk et al. (2019) fully align with ours, but only partially with other data. Considering that the characteristics of age groups participating in marathons can vary over time (Reusser et al., 2021), the partial consistency observed may be attributed to the larger participant pool in our study, which spanned 17 consecutive years, compared to their study, which only considered a single year. Similar results to those among male runners in our study were found in the study conducted by Nikolaidis et al. (2019). It also showed the lowest ES among female runners in the youngest and oldest groups, which is completely different from the results from our study. However, it is important to note that the oldest group in their study consisted of individuals older than 54, so we could not observe any further differences in this age range. Moreover, the distinct configuration of the running tracks in the Ljubljana and Vienna Marathons could have influenced pace variability in specific age groups, considering the morpho-physiological changes that occur with age (Hawkins & Wiswell, 2003; Tanaka & Seals, 2008; Visser, 2021). These changes will be described in the following text.

A study done by Nikolaidis and Knechtle (2019) which examined data spanning 2006 to 2016 from the New York City Marathon, revealed that older age groups exhibited less even pacing compared to younger ones, despite having similar performance levels. These performance levels were defined within each age group separately. The comparison between younger and older high-performing runners points to the distinction between faster and slower runners, as younger individuals are faster than their older counterparts (ibid.). Therefore, the researchers attributed these differences in PS to the age-related variation in physiological and training characteristics (Hawkins & Wiswell, 2003; Tanaka & Seals, 2008; Visser, 2021).

Given that VO_2max, lactate threshold, and running economy are crucial factors affecting endurance performance (Joyner, 1991; Joyner et al., 2011), it's worth noting that the former two decrease with age (Lee et al., 2019; Tanaka & Seals, 2008), while running economy remains stable in trained adults until around age 60 (dos Anjos Souza et al., 2023). It is considered that the main cause of performance decline in older runners is the gradual reduction of VO_2max, estimated to decrease by approximately 10% per decade due to central and peripheral changes (Hawkins & Wiswell, 2003; Tanaka & Seals, 2008). Morphological changes, such as decreased lean body mass and increased infiltration of fat into muscles, also have an impact on performance (Maharam et al., 1999; Visser, 2021). Age-related muscle atrophy becomes noticeable around the age of 50, with an annual loss of skeletal muscle mass ranging between 0.26% and 0.56% for individuals up to the age of 70 (Faulkner et al., 2008; Visser, 2021).

It has been suggested that aging leads to a decline in endurance exercise performance, primarily due to a decrease in the intensity and volume of exercise that can be sustained during training (Nikolaidis & Knechtle, 2019). Taking this evidence into consideration, older runners may face challenges in maintaining their training levels as they age.

There is evidence that aerobic capacity may help in maintaining speed during long-distance races (Nikolaidis & Knechtle, 2018b). Since the younger and older runners in our study demonstrated lower overall race speed compared to middle-aged runners, a lower aerobic capacity of these groups may be attributed to higher speed variability (Nikolaidis & Knechtle, 2018b). Younger runners, due to their relative youth, typically have less experience in comparison to middle-aged and older individuals, especially in long-distance running. This limited running experience can result in less consistent PS (Deaner et al., 2015). All of the aforementioned findings regarding age-related differences align with the results of our study, which showed higher speed variability throughout the race in runners aged up to 30 and 50 and older compared to middle-aged individuals.

Certain findings suggest that regular exercise plays a role in mitigating the decline of performance in experienced athletes who are at a master's age (>40 years) (Nikolaidis et al., 2018). This was supported by the observation that skilled master cross-country skiers employ PS comparable to those used by younger skiers, indicating the beneficial effects of regular physical activity (ibid.). These findings may partially explain the similarity in PS between the youngest and oldest age groups observed in our study, despite the morpho-physiological changes that come with aging.

The impact of increasing outside temperatures on runners varies depending on their age, with a greater negative impact observed in males aged 30–64 and females aged 40–64 (Weiss et al., 2022). Since older runners typically run at a slower pace than younger ones due to physiological and morphological changes associated with aging, they spend more time covering the same distance. Higher outside temperatures during a race may have a greater effect on their decrease in speed and overall PS.

Concerning the age-related variation in physiological and training characteristics (Hawkins & Wiswell, 2003; Tanaka & Seals, 2008; Visser, 2021), psychological factors such as overconfidence and competitiveness (Dechow & Allen, 2023; Hubble & Zhao, 2016) may not be the primary reasons for the faster race start observed in older runners compared to other age groups. Since running a marathon distance can cause severe muscle damage (Del Coso et al., 2013, 2017) and intolerable homeostatic disturbances (Berndsen, Lawlor, & Smyth, 2020; Smyth, 2021), it is not a race that can or should be undertaken frequently. Considering the gradual decline in performance as age advances, planning the PS from race to race can be challenging for older runners. In addition, each marathon experience brings unique sensations, differing from those at training sessions, which means that older runners may face their declining capabilities during the race.

8. LIMITATIONS OF THE STUDY AND FUTURE RESEARCH

One limitation of this study is the absence of supplementary information regarding other factors that might influence pacing, such as prior training regimen, experience in distance running and racing, or anthropometric characteristics. It should be noted that over the 17 years of the Vienna City Marathon, performance groups were established separately for sexes and races, and variations in weather conditions and participant numbers across different years could potentially impact the consistency of these divisions.

Conducting a comprehensive investigation into the PSs of half-marathons and marathons, encompassing additional data on previous training routines, motivation, running and racing experience, and anthropometric characteristics, is recommended. Moreover, since the weather has been changing slightly over the years, which may impact PSs, it may be worth exploring the possibility of making a more comprehensive subdivision of performance groups for each year. It would also be interesting to examine PS in non finishers since it is likely that they experienced difficulties due to an unsuccessful PS or suffered injuries that hindered their progress.

9. POTENTIAL SIGNIFICANCE AND PRACTICAL APPLICATION OF THE RESEARCH

The fact is that half-marathon and marathon running is a widespread physical activity worldwide with increasing participation each year. Since PS plays an important role in reducing the risk of significant homeostatic imbalances and achieving results in these disciplines, the analysis of these strategies has significant practical implications. Since a substantial portion of the participants in the Vienna City Marathon were international runners, we may eliminate the influence of a single nation. With a large and diverse sample, which likely represents the overall population of runners, the results can be generalized.

The novelties of this study are:

1. Analysis of a large sample of participants.
2. Analyses of half-marathon PSs were conducted by considering three factors: performance levels, sex and age – an approach adopted due to the limited availability of studies incorporating these specific factors in the context of half-marathons.
3. Comparison of half-marathon and marathon races held on the same day, on the same track, and under similar external conditions.
4. Analysis and comparison of half-marathon and marathon PSs were conducted based on three factors: performance level, sex and age.

The even pacing profile observed across different editions of the same race enables effective PS to be planned. The research results may provide valuable information to experts, coaches, athletes, and recreational runners when it comes to controlling fatigue during efforts to achieve the best possible race results. This information is specific to the length of the race, performance level, sex and age of the runners. The practical significance of this research lies in its ability to adopt a specific approach to the entire training process, individual training sessions, and races based on these subcategories. One potential approach is to focus on educating the specific subcategories that have shown insufficient knowledge and experience in PS during long-distance races. These particular subcategories include marathon runners in comparison to half-marathon runners; slower runners compared to faster ones; female runners compared to male runners in half-marathons; male runners compared to female runners in marathons; younger and older runners in contrast to male runners aged 40–59 and female runners aged 40–49, in half-marathons; younger and older runners compared to runners aged 30–49, in marathons.

By developing awareness and skill in managing fatigue during the training process and race, the risk of intolerable homeostatic disturbances and injuries could be reduced, allowing runners in every category to achieve better results and more positive subjective feelings during the race. Since the majority of participants in mass races are recreational runners, it is crucial to educate them properly so that running helps enhance their well-being in terms of health and quality of life rather than the opposite. This way, negative health consequences resulting from poor PS would be avoided, and the motivation of runners to continue engaging in running would be increased.

Besides theoretical education, a significant focus should be placed on training these runners to practice running at an even pace. This approach would allow them to utilize their energy efficiently and distribute it effectively from the very beginning of the race. Failure to do so increases the risk of early energy depletion or overly conservative pacing, which can negatively impact performance and lead to compensatory “end spurts”. Since a highly pronounced end spurt can pose health risks to runners, it is crucial to target certain subgroups based on race, performance level, sex, and age and provide them with the specific education they may need. The subgroups we compare that require particular attention regarding the health implications of an ES include half-marathon runners compared to marathon runners, slower runners compared to faster ones, younger runners compared to older ones, and female runners compared to male runners. Among these subgroups, the youngest male and female half-marathon runners, as well as the slowest runners in the half-marathon category, are considered the most critical.

Specific practical approach to individual training sessions for runners in these subcategories could be applied in the so-called "long runs" Long runs are typically performed once in a microcycle (which usually lasts 7 days), at a consistent pace, covering the longest distance and lasting the longest. During certain long runs, runners can practice appropriate target speed for a half-marathon or marathon race, depending on the performance level, sex and age of the runner.

Since achieving an even PS can be challenging to master, it is advisable to suggest beginners and less experienced recreational runners to maintain a negative PS. Specifically, they should avoid letting the adrenaline rush, the presence of other runners, and the initial feeling of being well-rested make them start the race at an excessively rapid pace. Instead, they should begin the race at a slower pace than the anticipated average race pace. This slower pace can be sustained throughout the initial one-third of the race, followed by a gradual speed increase in the second third to reach the planned average race pace. In the final one-third of the race, runners may consider increasing their pace a bit, either slightly exceeding the originally planned average race pace or maintaining their current pace if they find it appropriate. By adopting a negative PS, runners can help prevent homeostatic imbalances and potentially improve their overall performance, considering that achieving an even PS is more challenging to master.

Since PS also depends on external conditions, the research results could be significant in choosing a race where the runner could achieve the best result based on terrain configuration, weather forecast, time of year, etc. Additionally, they could provide the foundation for effective planning of PS during the race itself, resulting in an optimal pace and better final race result for the specific category of the runner.

Any runner from a specific category, equipped with the necessary knowledge and skills to plan an optimal PS, could choose a better pace at the beginning of the race to maintain the planned strategy until the end. Since pace depends on both internal and external factors at any given moment, the runner could better predict their capabilities in any given conditions and follow the planned PS to achieve the best result. Furthermore, the influence of other runners' paces on the race, which might be less favorable for maintaining optimal PS throughout the race, would be reduced.

10. CONCLUSIONS

10.1. Comparison of Pacing Strategies in the Half-Marathon and Marathon

Our findings indicate that both races displayed a positive PS with an ES, considering the overall sample. We observed a significant practical impact of the segment CS influence, although only a non-significant difference was noted between the fourth and fifth segments in the marathon. Half-marathon runners demonstrated a more evenly distributed PS throughout the race but exhibited a more pronounced ES compared to marathon runners. The difference in ACS between races was significant, but had limited practical significance.

Our findings also revealed that the influence of performance level had significant practical implications on ACS. Faster runners exhibited a more evenly distributed PS compared to slower runners in both races and among both sexes. Among men, half-marathoners displayed a more consistent PS compared to marathoners within each performance group, while among female runners, the opposite trend was observed. However, the difference in ACS between races was of minimal importance in both sexes.

The findings indicate that female runners exhibited smaller speed variability in longer race compared to male runners, whereas male runners displayed lower speed variability in shorter race. The disparities between sexes were more pronounced in the marathon compared to the half-marathon, but the difference between the races had minimal practical significance.

Male runners aged 40–59 and female runners aged 40–49 exhibited a more evenly distributed PS compared to younger and older groups in the half-marathon. The observed data showed a notably distinct situation within the group aged 30–49 in both sexes in the marathon, as they maintained a more evenly distributed PS than younger and older runners. Based on these findings, we can conclude that the specific age groups with the lowest ACS differed depending on the race type, and in the half-marathon, it also varied based on sex. Within each age group among male runners, more consistent PS was observed in the half-marathon compared to the marathon. However, all these differences had minimal practical significance. When it comes to female runners, the collected data showed no significant difference in ACS between the half-marathon and marathon races.

10.2. Analysis of Pacing Strategies in the Half-Marathon

A positive PS was observed in the overall sample of half-marathon runners, indicating that each segment's average speed was slower than the previous, except the last one, where a noticeable ES was observed. The practical significance of the differences in mean speed between segments was shown to be substantial.

Our findings revealed a positive PS with an ES in all performance groups and both sexes in the half-marathon. A notable practical significance of the segment CS influence was observed. In addition, the influence of the performance level on ACS was found to have a noteworthy level of practical significance as well. Faster runners demonstrated a more evenly distributed PS through the race compared to the slower runners also in both sexes, while slower runners exhibited a higher ES compared to the faster ones. Male runners had more evenly distributed PS compared to female runners within each performance group, but the differences between sexes had minimal practical significance.

A positive PS with an ES was observed in the half-marathon in both male and female runners. The significant practical impact of the influence of segment CS was observed, with each segment differing significantly from another in both sexes. Male runners demonstrated a more evenly distributed PS throughout the race compared to female runners, with smaller speed changes in most race segments.

Female runners exhibited a higher ES compared to male runners. However, the differences between sexes had trivial practical significance.

Our study found a positive PS with an ES in all age groups and both sexes during the half-marathon race. Male runners aged 40–59 and female runners aged 40–49 exhibited a more evenly distributed PS compared to the younger and older groups. The youngest age group showed the most pronounced ES in both sexes, with females showing a more pronounced effect. Female runners exhibited significantly greater speed variability throughout the race compared to male runners in the age groups of 40–69. In the age group of 30–39, the situation was reversed, showing slightly more speed changes in male runners than in female runners. However, all of these differences had minimal practical significance.

10.3. Analysis of Pacing Strategies in the Marathon

Our findings revealed positive PS with an ES in the overall sample of marathon runners. A significant difference and substantial practical impact were observed in the mean speed between segments, with each segment, except the last one, being slower than the previous one.

Our observations revealed a positive PS with an ES in most performance groups and both sexes in the marathon race. However, it is worth noting that an absence of an ES was only noticed in the male HL performance group. A significant practical impact was observed in the influence of segment CS, indicating a considerable difference in the CS between each segment for both sexes. The performance level of participants significantly influenced their ACS throughout the race, with medium practical significance, irrespective of sex. Faster runners demonstrate a greater consistency in their pace compared to slower runners. Female runners generally exhibited a more evenly distributed PS within each performance group, although the practical significance of differences between sexes was limited.

The study observed a positive PS with an ES in both male and female marathon runners. A significant influence of segment CS was observed, with a medium practical significance, as each segment showed notable differences from one another in both sexes. Female runners showed a more evenly distributed PS compared to their counterparts, with lesser variations in speed throughout each segment of the race. Moreover, female runners displayed a greater ES when compared to male runners. Nevertheless, the disparities between the sexes held minimal practical significance.

A positive PS with an ES across all age groups and both sexes was observed. The middle-aged group (30–49 years old) displayed a more evenly distributed PS compared to the younger and older groups, regardless of sex. The youngest group of male runners showed the most pronounced ES, while both the oldest and youngest groups of female runners exhibited a higher ES compared to the other age groups. Male runners showed significantly greater speed variability than female runners across all age groups up to 69 years. However, the practical significance of all these differences was found to be trivial.

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Biography

Ristanović (Dušan) Ljubica, born on September 8, 1995, in Smederevo, Republic of Serbia, completed Živomir Savković elementary school in Kovačevac as the “highest achieving pupil”. She graduated from the Mladenovac Gymnasium in 2014.

She obtained her Bachelor’s degree at the University of Belgrade, Faculty of Sport and Physical Education in the academic year 2017/18, earning the honors of “highest achieving undergraduate student”. Subsequently, she completed her Master's studies in the academic year 2018/19 and enrolled in the Doctoral studies program at the same school. Additionally, alongside these studies, she completed her Master’s studies at the University of Belgrade, Faculty of Medicine, in the academic year 2020/21. During her Master's studies, she had the opportunity to enhance her professional development by participating in the ERASMUS+ project. As part of this project, she spent one semester at the University of Sports Science in Rome, “Foro Italico”. As part of her Doctoral studies, she furthered her professional development through the same project, spending one semester at the University of Granada, Faculty of Sport Sciences, in the academic year 2022/23.

During her Bachelor studies in 2016, she spent four months in Alaska, USA, through the “Work and Travel” program for students. During this period, she worked outside her field of study as a hostess, assistant cook, and cashier, gaining valuable real-life experience.

She trained in karate for 10 years with the Mladenovac Karate Club and attained the rank of “Master of Karate” with a 1st Dan Black Belt in 2011. She also earned national and international medals for her achievements in the sport.

Currently, she is employed temporarily as teaching assistant at the Faculty of Sport and Physical Education Department of Sports and Recreation Theory and Methodology. She has been involved in teaching as an associate (demonstrator) since the academic year 2018/19. Since March 2023, she has been working as a coach at the BRAVEHEARTS recreational club. Her most extensive practical experience was gained at the Belgrade Running Club, where she worked as a coach for recreational runners for six years. Since 2017, she has been actively involved in providing individual training sessions to recreational athletes in the field of fitness.

Биографија

Ристановић (Душан) Љубица, рођена 08.09.1995. године у Смедереву, република Србија, завршила основну школу „Живомир Савковић“ у Ковачевцу, као „ђак генерације” и средњу школу Гимназију у Младеновцу са одличним успехом, 2014. године.

На Универзитету у Београду – Факултету спорта и физичког васпитања је дипломирала школске 2017/18. године као „студент генерације“. На истом факултету је завршила Мастер академске студије школске 2018/19 и уписала Докторске академске студије. Упоредо са овим студијама је завршила Мастер академске студије, школске 2020/21, на Универзитету у Београду – Медицинском факултету. Током ових Мастер академских студија је преко ERASMUS+ пројекта провела један семестар, школске 2019/20, на Универзитету за спортске науке у Риму – факултету „Форо Италико“, на стручном усавршавању. Током Докторских академских студија је преко истог пројекта провела један семестар, школске 2022/23, на Универзитету у Гранади – Факултету за спортске науке, на стручном усавршавању.

Током основних академских студија, 2016. године, провела је четири месеца на Аљасци у САД-у, преко „Work and Travel“ програма за студенте. У току овог периода је стекла значајно животно искуство, радећи ван своје струке, као хостеса, помоћни кувар и касирка.

Тренирала је карате 10 година у карате клубу „Младеновац“ и носилац је црног појаса 1. Дан и титуле „Мајстор каратеа“. Освајач је националних и међународних медаља у овом спорту. Од тада се рекреативно бави трчањем, а последњих пет година и триатлоном. Редовно учествује на тркама различитих дистанци.

Тренутно је запослена на одређено време, као асистент, на Факултету спорта и физичког васпитања, на Катедри за теорију и методологију спорта и рекреације. На истој Катедри је била ангажована у настави као сарадник ван радног односа (демонстратор) од школске 2018/19. године. Ради као тренер у „BRAVEHEARTS“ рекреативном клубу од марта 2023. године, а највеће практично искуство је стекла у „Београдском тркачком клубу“, где је радила 6 година као тренер рекреативних тркача. Поред групних тренинга, ради и индивидуалне тренинге са рекреативцима у фитнесу од 2017. године.

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Потпис аутора

У Београду, ________________________

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Approval of the Ethics Committee

УНИВЕРЗИТЕТ У БЕОГРАДУ
ФАКУЛТЕТ СПОРТА И ФИЗИЧКОГ ВАСПИТАЊА
02 Бр 385/24-2
01. 3. 2024 год
БЕОГРАД, Благоја Паровића 156

UNIVERSITY OF BELGRADE
FACULTY OF SPORT AND PHYSICAL EDUCATION
ETHIC COMMITTEE

Subject: Approval of Protocol no. 385/24-1 from 20.02.2024, submitted by Dr Stanimir Stojiljković, full professor, University of Belgrade, Faculty of Sport and Physical Education. Ethics Committee of the Faculty of Sport and Physical Education gives:

APPROVAL

For conducting research entitled „Pacing strategy in half-marathon and marathon based on performance level, sex and age". The research will be carried out by a team of researchers consisting of: Ljubica Ristanović (principal researcher), assistant at the University of Belgrade, Faculty of Sports and Physical Education, Dr. Stanimir Stojiljković, full professor at the University of Belgrade, Faculty of Sports and Physical Education and Ivan Ćuk, assistant professor at the University in Belgrade, Faculty of Sports and Physical Education.

REASONING

Based on the submitted documents for the research proposal, Ethics Committee of Faculty of Sport and Physical Education, University of Belgrade, concluded that both the concept and the planning of the research and implementation of the obtained results follow the principles in compliance with ethical standards and that it presents no risk to the participants.

Therefore, Ethics Committee of the Faculty approves conducting of the planned research project „Pacing strategy in half-marathon and marathon based on performance level, sex and age".

In Belgrade, 22. 02. 2024.

Članovi

1. Ph. D. Ana Orlić, full professor
2. Ph. D. Marina Đorđević-Nikić, full professor
3. Ph. D. Lidija Moskovljević, full professor

Сагласност етичке комисије

УНИВЕРЗИТЕТ У БЕОГРАДУ
ФАКУЛТЕТ СПОРТА И ФИЗИЧКОГ ВАСПИТАЊА
02 Бр 385/24-2
01. 3. 2024 год.
БЕОГРАД, Благоја Паровића 156

UNIVERZITET U BEOGRADU
FAKULTET SPORTA I FIZIČKOG VASPITANJA
ETIČKI KOMITET

Predmet - Na zahtev zaveden pod brojem 02-385/24-1 od 20. 02. 2024. godine, koji je podneo dr Stanimir Stojiljković, redovni profesor na Univerzitetu u Beogradu – Fakultetu sporta i fizičkog vaspitanja, Etički komitet Univerziteta u Beogradu – Fakulteta sporta i fizičkog vaspitanja daje

S A G L A S N O S T

Za sprovođenje istraživanja pod naslovom „Strategija tempa trčanja polumaratona i maratona u zavisnisnoti od takmičarske uspešnosti, pola i starosti (Pacing strategy in half-marathon and marathon based on performance level, sex and age)". U istraživanje učestvuje tim istraživača u sastavu: Ljubica Ristanović (glavni istraživač), asistent na Univerzitetu u Beogradu – Fakultetu sporta i fizičkog vaspitanja, dr Stanimir Stojiljković, redovni profesor na Univerzitetu u Beogradu – Fakultetu sporta i fizičkog vaspitanja i Ivan Ćuk, docent na Univerzitetu u Beogradu – Fakultetu sporta i fizičkog vaspitanja.

O b r a z l o ž e nj e

Na osnovu uvida u projekat istraživanja, Etički komitet Fakulteta iznosi mišljenje da se, kako u konceptu tako i u planiranju realizacije istraživanja i primene dobijenih rezultata, polazilo od principa koji su u skladu sa etičkim standardima, čime se obezbedjuje zaštita ispitanika od mogućih povreda njihove psiho-socijalne i fizičke dobrobiti.

U skladu sa iznetim mišljenjem Etički komitet Fakulteta daje saglasnost za realizaciju istraživanja „Strategija tempa trčanja polumaratona i maratona u zavisnisnoti od takmičarske uspešnosti, pola i starosti (Pacing strategy in half-marathon and marathon based on performance level, sex and age)".

U Beogradu, 22. 02. 2024.

Članovi

1. dr Ana Orlić, redovni profesor
2. dr Marina Đorđević Nikić, redovni profesor
3. dr Lidija Moskovljević, redovni profesor

Published research

frontiers | Frontiers in Psychology

TYPE Original Research
PUBLISHED 21 December 2023
DOI 10.3389/fpsyg.2023.1273451

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OPEN ACCESS

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RECEIVED 06 August 2023
ACCEPTED 21 November 2023
PUBLISHED 21 December 2023

CITATION
Ristanović L, Cuk I, Villiger E, Stojiljković S, Nikolaidis PT, Weiss K and Knechtle B (2023) The pacing differences in performance levels of marathon and half-marathon runners. *Front. Psychol.* 14:1273451.
doi: 10.3389/fpsyg.2023.1273451

The pacing differences in performance levels of marathon and half-marathon runners

Ljubica Ristanović[1], Ivan Cuk[1], Elias Villiger[2], Stanimir Stojiljković[1], Pantelis T. Nikolaidis[3,4], Katja Weiss[5] and Beat Knechtle[5,6]*

[1]Faculty of Sport and Physical Education, University of Belgrade, Belgrade, Serbia, [2]Klinik für Allgemeine Innere Medizin, Kantonsspital St. Gallen, St. Gallen, Switzerland, [3]Exercise Physiology Laboratory, Nikaia, Greece, [4]School of Health and Caring Sciences, University of West Attica, Athens, Greece, [5]Institute of Primary Care, University of Zurich, Zurich, Switzerland, [6]Medbase St. Gallen Am Vadianplatz, St. Gallen, Switzerland

Introduction: Many studies indicate a considerable impact of optimal pacing on long-distance running performance. Given that the amount of carbohydrates in metabolic processes increases supralinearly with the running intensity, we may observe differences between the pacing strategies of two long-distance races and different performance levels of runners. Accordingly, the present study aimed to examine the differences in pacing strategies between marathon and half-marathon races regarding the performance levels of runners.

Methods: The official results and split times from a total of 208,760 (marathon, $N = 75{,}492$; half-marathon, $N = 133{,}268$) finishers in the "Vienna City Marathon" between 2006 and 2018 were analyzed. The percentage of the average change of speed for each of the five segments (CS 1–5), as well as the absolute change of speed (ACS) were calculated. The CS 1–5 for the marathon are as follows: up to the 10th km, 10th – 20th km, 20th – 30th km, 30th – 40th km, and from the 40th km to the 42.195 km. For the half-marathon, the CS 1–5 are half of the marathon values. Four performance groups were created as quartiles of placement separately for sexes and races: high-level (HL), moderate to high-level (MHL), moderate to low-level (MLL), and low-level (LL).

Results: Positive pacing strategies (i.e., decrease of speed) were observed in all performance groups of both sex and race. Across CS 1–5, significant main effects ($p < 0.001$) were observed for the segment, performance level, and their interaction in both sex and race groups. All LL groups demonstrated higher ACS (men 7.9 and 6.05%, as well as women 5.83 and 5.49%, in marathon and half-marathon, respectively), while the HL performance group showed significantly lower ACS (men 4.14 and 2.97%, as well as women 3.16 and 2.77%, in marathon and half-marathon, respectively). Significant main effects ($p < 0.001$) for the race were observed but with a low effect size in women ($\eta^2 = 0.001$).

Discussion: Better runners showed more even pacing than slower runners. The half-marathoners showed more even pacing than the marathoners across all performance groups but with a trivial practical significance in women.

Изјава о ауторству

Име и презиме аутора: Љубица Ристановић

Број индекса: 5006/2019

Изјављујем

да је докторска дисертација под насловом

„Pacing strategy in half-marathon and marathon based on performance level, sex and age“ („Стратегија темпа трчања полумаратона и маратона у зависности од такмичарске успешности, пола и старости“)

- резултат сопственог истраживачког рада;
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Изјава о истоветности штампане и електронске верзије докторског рада

Име и презиме аутора: Љубица Ристановић

Број индекса: 5006/2019

Студијски програм: Експерименталне методе истраживања хумане локомоције

Наслов рада: **„Pacing strategy in half-marathon and marathon based on performance level, sex and age“ („Стратегија темпа трчања полумаратона и маратона у зависности од такмичарске успешности, пола и старости“)**

Ментори:

1. др Станимир Стојиљковић, редовни професор
2. др Иван Ћук, доцент

Изјављујем да је штампана верзија мог докторског рада истоветна електронској верзији коју сам предао/ла ради похрањивања у **Дигиталном репозиторијуму Универзитета у Београду.**

Дозвољавам да се објаве моји лични подаци везани за добијање академског назива доктора наука, као што су име и презиме, година и место рођења и датум одбране рада.

Ови лични подаци могу се објавити на мрежним страницама дигиталне библиотеке, у електронском каталогу и у публикацијама Универзитета у Београду.

Потпис аутора

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Изјава о коришћењу

Овлашћујем Универзитетску библиотеку „Светозар Марковић“ да у Дигитални репозиторијум Универзитета у Београду унесе моју докторску дисертацију под насловом:

„Pacing strategy in half-marathon and marathon based on performance level, sex and age“ („Стратегија темпа трчања полумаратона и маратона у зависности од такмичарске успешности, пола и старости“)

која је моје ауторско дело.

Дисертацију са свим прилозима предао/ла сам у електронском формату погодном за трајно архивирање.

Моју докторску дисертацију похрањену у Дигиталном репозиторијуму Универзитета у Београду и доступну у отвореном приступу могу да користе сви који поштују одредбе садржане у одабраном типу лиценце Креативне заједнице (Creative Commons) за коју сам се одлучио/ла.

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1. **Ауторство**. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце, чак и у комерцијалне сврхе. Ово је најслободнија од свих лиценци.

2. **Ауторство – некомерцијално**. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце. Ова лиценца не дозвољава комерцијалну употребу дела.

3. **Ауторство – некомерцијално – без прерада**. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, без промена, преобликовања или употребе дела у свом делу, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце. Ова лиценца не дозвољава комерцијалну употребу дела. У односу на све остале лиценце, овом лиценцом се ограничава највећи обим права коришћења дела.

4. **Ауторство – некомерцијално – делити под истим условима**. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце и ако се прерада дистрибуира под истом или сличном лиценцом. Ова лиценца не дозвољава комерцијалну употребу дела и прерада.

5. **Ауторство – без прерада**. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, без промена, преобликовања или употребе дела у свом делу, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце. Ова лиценца дозвољава комерцијалну употребу дела.

6. **Ауторство – делити под истим условима**. Дозвољавате умножавање, дистрибуцију и јавно саопштавање дела, и прераде, ако се наведе име аутора на начин одређен од стране аутора или даваоца лиценце и ако се прерада дистрибуира под истом или сличном лиценцом. Ова лиценца дозвољава комерцијалну употребу дела и прерада. Слична је софтверским лиценцама, односно лиценцама отвореног кода.