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Systematic Review

Change in Spatiotemporal Parameters During Running at Different Degrees of Inclination: Systematic Review

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Abstract: Background:Running is one of the simplest and most popular forms of exercise. Biomechanical evaluation of running is one of the elements of evaluating running technique and, consequently, improving sports performance. Running uphill and downhill is one of the components of daily running but also an element of training used by recreational runners. The aim of this study is to optimize running training and minimize the risk of injury by identifying changes in the spatiotemporal structure of running at different inclinations. Methods: The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed. The protocol has been registered on the international platform INPLASY under the number INPLASY202430094U2. The search was conducted up to 30 March 2024 using the Scopus, PubMed, and Web of Science databases. Results: Spatiotemporal parameters were most frequently analyzed at 2.8–3.35 m/s velocities and inclinations in the range of −11% to 11%. Decreases in stride length (SL) and flight time (FT), and increases in step frequency (SF) were the most frequently reported changes from all parameters analyzed as a function of inclination and velocity. Significant increases or decreases in individual parameters were more often observed for positive inclination values than negative ones. Conclusions: The heterogeneous results of the study limit the possibility of determining the changes that occur in the spatiotemporal structure of the run under the impact of different inclinations. The variation in the results for negative inclination values indicates the different characteristics of running uphill and downhill. However, for uphill running, SF, SL, and FT are closely related to the increase in inclination.

Keywords: spatiotemporal parameters; inclination; velocity; recreational runners

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1. Introduction

Running is one of the most popular forms of physical activity, evidenced by the number of runners worldwide. It is considered that as much as 36% of the population in Europe runs recreationally. Although running is considered a simple motor activity, it requires complex motor integration of all body segments [1]. In addition, high running loads are often associated with injuries such as fatigue fractures of the tibia, plantar fasciitis, or patellofemoral pain [2]. It is estimated that each year as many as 80% of runners suffer an injury [3]. To prevent these injuries, understanding the correct running pattern is key [4].

Therefore, the biomechanics of running has been a major interest for researchers in human locomotion sciences due to its uniqueness and complexity [5,6].

Indeed, analyzing biomechanical variables might provide a better understanding of the runners' motor actions [4,7]. The dynamics of change and the kinematic structure of running are characterized by a cycle that consists of a support phase and a flight phase [8]. Previous studies report that effective running is characterized by a cycle in which the flight phase is about 65% and the support phase is about 35% [7]. Step length, contact time, flight time, step frequency, or step time are parameters that regulate and optimize the above-mentioned cycle [9,10]. Appropriate proportions of those variables in the spatiotemporal structure optimize the dynamics of running, increasing its efficiency [7]. The parameters can also be important predictors of injury risk [11]. Step width can cause changes in lower limb biomechanics. It has been observed that an increased step width can lead to decreased hip adduction angle and heel roll or peak knee inversion. Conversely, an increased peak hip adduction angle may be one of the factors that causes patellofemoral pain [12]. In addition, it has been shown that an increased stride frequency can significantly reduce stress on the knee and hip joints, which can result in a lower risk of running injuries [11]. On the other hand, a literature review conducted by Brindle et al. [3] found no significant correlations between spatiotemporal parameters and injury history. In contrast, according to other studies, stepping too long caused a disruption in the synchrony of the knee and ankle joint, which increased the load on the entire limb and thus the risk of injury [13].

Examples of the spatiotemporal parameters may include distance and running speed, running stride width and length, or stride frequency. It has been suggested that they may be related to injury risk [3]. Step width can cause changes in lower limb biomechanics. It has been observed that an increased step width can lead to a decreased hip adduction angle and heel roll or peak knee inversion. Conversely, an increased peak hip adduction angle may be one of the factors that causes patellofemoral pain [12]. In addition, it has been shown that an increased stride frequency can significantly reduce stress on the knee and hip joints, which can result in a lower risk of running injuries [11]. On the other hand, a literature review conducted by Brindle et al. [3] has not found any significant correlations between spatiotemporal parameters and injury history.

According to previous research, maximum speed results from the optimal relationship (combination) between stride length and stride frequency [14]. Similar findings were reported by Overan et al. [15], who characterized several runners based on their stride length and frequency, describing a strong relationship between both parameters. Moreover, several authors reported a curvilinear increase in stride length and cadence with running [15–20]. In the literature, available reports on this matter also described the negative curvilinear relationship of stance phase with increasing speed [15,18,21–25]. The phase of flight, however, was reported to grow with increasing running speed, although at high speeds, it stabilized at a constant level [15]. Compared to running at zero incline, few studies have analyzed spatiotemporal parameters at different inclinations. In the review article on the biomechanics of running on downhill and uphill runs published by Vernillo et al., only nine papers were included in the spatiotemporal analysis of running [5], which emphasizes the lack of details accessible on the topic.

Vernillo et al. [5] points out that most studies have focused only on analyzing horizontal running. Running events have often been associated with running on flat terrain such as marathons, half-marathons, or running on an athletic treadmill. However, ultra-marathons, which involve running long distances at different incline angles, have become very popular in recent years [5]. Indeed, running uphill and downhill should demand a different effort and biomechanical behavior than running on a flat level. Thus, understanding the variation in spatiotemporal parameters at several inclinations might support the runner's development and training process by providing detailed feedback on the variables to improve [26]. Therefore, the current study aims to provide, in detail, an overview of the current literature on assessing the spatiotemporal parameters of running under the influence of different gradients.

2. Methods

2.1. Data Sources and Search Strategy

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [27]. The protocol was registered with the International Platform of Registered Systematic Review and Meta-Analysis Protocols INPLASY on 23 March 2024 (INPLASY202430094U2). The search was conducted up to 30 March 2024 by two independent authors (M.P. and C.F.) using the Scopus, PubMed, and Web of Science databases. If there were discrepancies between the two authors, a third independent reviewer, W.P., was consulted who, based on careful analysis, decided whether to include or exclude the disputed papers. The following terms were used: (run* OR running) AND (spatial* OR temporal* OR time* OR space* OR kinematic* OR "kinematic* parameter*" OR "step time" OR "space time parameter*" OR "spatiotemporal parameter*" OR phase* OR "running phase*") AND (slope* OR "different* slope*" OR gradient* OR inclination* OR "different* inclination*") AND (athlete* OR runner*). To complete the database with missing items, a manual search was conducted using Google Scholar.

2.2. Eligibility Criteria

The inclusion criteria were: (1) adult recreational runners who do not train competitively, (2) men and women who were healthy and had no injuries at the time of the study, (3) studies analyzing the spatiotemporal parameters of running with a variable gradient and constant speed, (4) research containing inclination comparisons between −20% to 20%, (5) only original and full-text studies written in English, Polish, or Portuguese, and (6) studies published in scientific journals between 1 January 2000 and 30 March 2024.

2.3. Quality Assessment

The risk of bias was conducted by two independent authors using the Joanna Briggs Institute (JBI) critical appraisal checklist for analytical cross-sectional studies [28]. The instrument evaluates the risk of bias using eight criteria, classified into the following categories: yes, no, and unclear. The overall risk of bias resulted from the eight criteria assessed. Studies that were complete, or those that missed one element, were classified as low risk of bias, studies that missed two to three elements were rated as moderate risk of bias, while studies that missed four or more elements were rated as high risk of bias.

3. Results

3.1. Study Selection

Figure 1 illustrates the flowchart of the study selection procedure. The total number of articles resulting from the initial search was 1114. Four documents were found manually and included in the data selection process, resulting in a total of 1119 documents being selected. After that, duplicates were automatically removed (n = 415). The remaining 704 articles were analyzed based on the title and abstract. Publications unrelated to biomechanics or running kinematics were rejected at this stage, which resulted in the total number of 38 remaining items. In the next step, all the articles included in this stage were read for verification and qualification for review. Based on the established inclusion and exclusion criteria, 23 articles were excluded, with the remaining 15 documents included were for analysis.

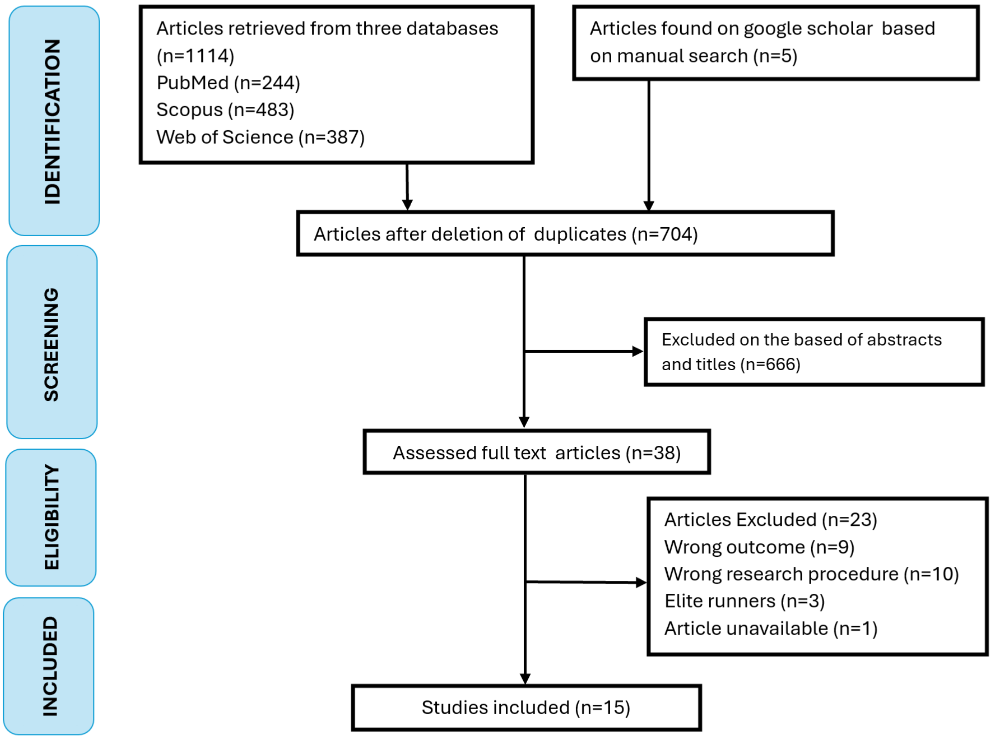

Figure 1. Flowchart of the study selection process.

3.2. Assessment of Risk of Bias

Seven studies (46.7%) were classified as having a low risk of bias and eight studies (53.3%) were classified as carrying a "moderate" risk of bias (Table 1). The reason for this high percentage was the lack of precise characterization of bias factors and the lack of clearly defined strategies for dealing with them. The authors were very precise and meticulous in describing the research procedure, but they did not equally define the interfering factors and strategies for dealing with them. Fourteen "Unclear" responses related to questions about the characteristics of disruptions and how to deal with them. "No" answers were used twice and also related to the above questions. One "Unclear" answer concerned how the statistical analysis was conducted.

Table 1. Assessment of risk of bias.

Study	Were the Criteria for Inclusion in the Sample Clearly Defined?	Were the Study Subjects and the Setting Described in Detail?	Was the Exposure Measured in a Valid and Reliable Way?	Were the Study Subjects and the Setting Described in Detail?	Were Confounding Factors Identified?	Were Strategies to Deal with Confounding Factors Stated?	Were the Outcomes Measured in a Valid and Reliable Way?	Was Appropriate Statistical Analysis Used?	Overall Risk of Bias
DeVita et al. (2008) [29]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Gottschall & Kram (2005) [30]	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Moderate
Lemire et al. (2023) [31]	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Moderate
Lussiana et al. (2015) [32]	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Moderate
Lussiana et al. (2013) [33]	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Moderate
Padulo et al. (2012) [34]	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Unclear	Moderate
Padulo et al. (2013) [35]	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Moderate
Padulo et al. (2023) [36]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Park et al. (2019) [37]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Snyder et al. (2011) [38]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Telhan et al. (2010) [39]	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Moderate
García-Pinillos et al. (2019) [40]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Dickinson et al. (2020) [41]	Yes	Unclear	Yes	Yes	Unclear	Unclear	Yes	Yes	Moderate
Thomson et al. (2021) [42]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low
Zignoli et al. [43]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Low

3.3. Intervention Characteristics

Fifteen papers were included in the analysis. Each study considered reported the assessment of at least one spatiotemporal parameter on at least two different gradients. The characteristics of each study are shown in Table 2. Overall, the total number of participants assessed was 151. The studies that included women (n = 31) did not distinguish separate outcomes by sex [29,30,36,39,43]. Above that, four articles did not specify the participants by sex [35,37,41,42]. The largest sample size was that of Telhan et al. [39] and Lemire et al. [31] (n = 19). The smallest sample size was found in the study by Snyder et al. [38] (n = 9). The study with the oldest group of participants was conducted by García-Pinillos et al. [40] (34.40 ± 6.93 years), and the trial with the youngest number of participants was conducted by Padulo et al. [34] (21.83 ± 1.33 years). Analysis of kinematic parameters at different inclinations was the main focus of work for five publications [33,34,37,38,40]. For the other authors [29–32,35,39], the analysis of spatiotemporal parameters at different inclinations was only part of the overall research protocol focusing on ground reaction forces [30,31,39] running energetics [29,35], or leg stiffness [32].

The studies included only research related to amateur-level running. However, the experience of the runners varied. Some authors included individuals training a minimum of 30 km per week [32,33,36,39,42]. For other authors, the sufficient criterion was running at least 10 km per week [37] or completing one training session [31]. Some authors included runners at a relatively high amateur level. These were individuals whose speeds achieved during competitions at distances from 5 km to a marathon reach 15 km/h and often exceed this [35,38,41]. Other authors included high-fitness runners who train regularly but without specifying their sports level [29,30,34,43].

Table 2. Characteristics of the group.

Study	Sample (n)	Age (Years)	Height (cm)	Weight (kg)
DeVita et al. (2008) [29]	8M, 5F	22.3 ± 2.8	174 ± 10	69.9 ± 13.2
Gottschall and Kram (2005) [30]	5M, 5F	30.35 ± 5.09	172 ± 6	62.56 ± 7.59
Lemire et al. (2023) [31]	19ND	34 ± 10	175 ± 10	68.5 ± 12.2
Lussiana et al. (2015) [32]	14M	23.4 ± 4.4	177.5 ± 5.2	69.5 ± 5.3
Lussiana et al. (2013) [33]	14M	23.4 ± 4.4	177.5 ± 5.2	69.5 ± 5.3
Padulo et al. (2012) [34]	8ND	21.83 ± 1.33	171 ± 4.50	70.70 ± 3.88
Padulo et al. (2013) [35]	18M	33.0 ± 8.5	171 ± 4	62.6 ± 5.2
Padulo et al. (2023) [36]	22M, 3F	38.0 ± 11	173 ± 7	63 ± 8
Park et al. (2019) [37]	15ND	25.6 ± 4.27	177.0 ± 5.0	75.38 ± 5.02
Snyder et al. (2011) [38]	9M	28.5 ± 4.1	leg length: 0.95 ± 0.04	69.1 ± 5.3
Telhan et al. (2010) [39]	9F, 10M	F: 23.9 ± 2.5 M: 26.6 ± 5.9	F: 166.4 ± 6.2 M: 180.5 ± 5.2	F: 56.2 ± 4.8 M: 74.2 ± 8.1
García-Pinillos et al. (2019) [40]	12M	34.40 ± 6.93	174.08 ± 6.59	72.67 ± 5.30
Dickinson et al. (2020) [41]	13M	ND	181.10 ± 6.59	71.0 ± 9.0
Thomson et al. (2021) [42]	10M	28 ± 5	180.0 ± 6.0	63.0 ± 8.0
Zignoli et al. (2023) [43]	11M, 9F	25 ± 6	BMI = 20.76 ± 1.75 $\frac{\mathrm{kg}}{\mathrm{m}^2}$	

F—Female, M—Male, ND—not defined, BMI—Body Mass Index.

3.4. Main Findings

The purpose of this study was to review the existing literature on how the spatiotemporal structure of running changes under different incline conditions. All included studies were characterized in terms of instruments used, research protocol, parameters measured, gradient and velocity, and main results to verify the effect of inclination on spatiotemporal parameters (Table 3). Understanding the research protocols and methods used seems to be essential in evaluating the effect of slope on spatiotemporal parameters.

3.4.1. Instruments

An element common to all the tests conducted is the use of a mechanical treadmill in the research protocol. Only DeVita et al. [29] conducted tests using a ramp. The kinematic analysis of running was usually carried out using optical systems [32,33,40,43], vision systems [29,34,35,37,39], and force platforms [30,31,38]. Pressure insoles for shoes were used by only one author [42] as was the measuring wheel attached to the treadmill belt [41]. All research procedures were well and meticulously planned. The goals and research concepts of the various authors resulted in wide variations in data recording and research methods. The length of trials varied and depended on many factors. The longest trial was conducted by Lussiana et al. [32]. In their experiment, participants performed a treadmill run for seven series of 5 min each, at a speed of 10 km/h and with independent step length and frequency, for a total of 14 series over a period of one week. Each of these series was conducted at different inclinations, starting at −8% and ending at 8%. The shortest trial, on the other hand, was completed before Gottschall et al. [30]. Each of his trials lasted only 1 min, and data were collected for the last 10 s of each trial.

3.4.2. Parameters Tested

In all the included papers, the authors measured a total of ten spatiotemporal parameters: stride length (SL), contact time (CT), swing time (ST), duty factor (DF), aerial time (AT), step frequency (SF), step length (StL), relative step length (RStL), step angle (SA), and flight time (FT). The number of parameters was closely related to the main focus of each paper. The most spatiotemporal parameters at different inclinations were measured by Lemire et al. [31], who analyzed a total of six parameters: CT, AT, DF, SF, StL, and RStL. Five parameters were analyzed by Gottschall et al. [30] (SF, SL, CT, ST, DF) and García-Pinillos et al. [40] (CT, FT, SA, SF, StL). The great majority of authors analyzed two to four spatiotemporal parameters [32–37,39,41,43]. DeVita et al. [29], Snyder et al. [38], and Thomson et al. [42] examined one parameter each. The former performed the analysis for SL and the latter for SF. At the same time, these were the most frequently analyzed parameters among all authors.

Of all the criteria analyzed, the greatest variation occurs for the slope used. The researchers, most often, adopted a slope between −11% and 11%. Only three authors used an inclination beyond the above-described scale. Lemire et al. [31], Gotschall et al. [30], and Park et al. [37] conducted studies at the following gradients: −17.6%, 17.6%, −15.8%, and 15.8%. However, there was a lack of consistency in all the research protocols evaluated as to the choice of slope values. The vast majority of authors used the capabilities of the mechanical treadmill and available equipment to analyze uphill and downhill running at the same incline [29–33,38,40]. Some researchers focused their attention solely on uphill running [34,35,40]. Only Park et al. [37] analyzed the uphill run without analyzing the uphill run on the same gradients. The most problematic aspect of selecting individual studies was the lack of consistency in the exact value of gradients in the selected protocols. In the 15 included articles, the total number was 23 gradients. The smallest difference in the applied inclinations for two different authors was 0.2%. The only common inclination for all authors except DeVita et al. [29] and Zignoli et al. [43] was a reference to a 0% inclination value.

3.4.3. Effect of Inclinations on Spatiotemporal Parameters

Velocity 2.8 m/s

The lowest and most commonly used velocity in the analysis of spatiotemporal parameters was 2.8 m/s [31–33,38]. Despite using different inclinations, three studies found no statistically significant differences for CT [31–33]. In the study of Lemire et al. [31], the difference between the extreme inclination was only 10 ms. In the study by Lussiana et al. [32,33], the CT decreased from 308 ms to 301 ms between −8% and 8%. SF was analyzed by all four authors who used a velocity of 2.8 m/s [31–33,38]. Three studies noted statistically significant changes in SF with increasing inclination ($p < 0.05$). Lemire et al. [31] observed a clear difference only at an inclination of 17.6%, yielding an SF value of 2.81 Hz. Lussiana et al. [32,33] observed a steady increase in SF. In her study, she obtained a 0.12 Hz difference for a comparison of −8% vs. 8%. Only Snyder et al. [38] did not observe significant changes in SF when changing the inclinations. Parameters such as AT, StL, and RStL were investigated only by Lemire et al. [31]. Statistical analysis showed a statistically significant ($p < 0.05$) decrease in AT and an increase in DF with each change in inclination. AT decreased by 0.2 s reaching a value of 0.7 s at an inclination of 17.6%. DF increased by 6.6% between extreme inclination values. StL and RStL decreased significantly only when the inclination increased from 0% to 17.6%. FT was investigated only by Lussiana et al. [32,33] who noted significant differences in this parameter with increasing inclination ($p < 0.05$). A constant CT value of 71 ms was maintained for inclinations −8% and −5%. Only at inclinations of −2%, 0%, and 2% was there a noticeable reduction in CT, reaching 63 ms for −2% and 55 ms for inclinations of 0% and 2%. At inclinations of 5% and 8%, the execution time (FT) began to increase, reaching corresponding values of 56 ms and 59 ms.

Velocity 3.0–3.35 m/s

The range of velocities mentioned is taken from the six studies included in this review [29,30,37,38,40,42]. SL analysis was conducted by four researchers, who presented different results. DeVita et al. [29] observed an increase in the SL by 4% between an inclination of −10% and 10% ($p < 0.05$). Gottschal et al. [30] observed a significant relationship comparing conditions of 0% vs. 15.8%. Telhan et al. [39] also observed a statistically significant shortening, but only for an increase in the inclination from 0% to 7%. Park et al. [37], in analyzing the parameters only on the minus values of the inclination −15.8%, −10%, and 0%, did not notice statistically significant differences for this parameter. SF was investigated in four studies [30,37,39,40]. Gottschal et al. [37] observed a significant increase in SF of nearly 4%, while Telhan et al. [39] observed an increase of nearly 1.2%. Park et al. [37] observed no significant changes for this parameter. However, a significant decrease for CT of 10 ms was observed by Park et al. [37] with a change in the inclination from −15.8% to −10.5%. A slight increase was also observed. On the other hand, a slight increase with an increase in the inclination to 3% was observed by Garcia et al. [40]. At the inclination of 11%, CT noticeably shortened. Thomson et al. [42] on the other hand observed a linear increase in CT for positive gradients ($p < 0.001$). However, he noted that the highest CT was measured for the sample at the slope −5%. ST was measured in two studies [30,37], but neither of them showed significant changes in this parameter. DF was measured only by Gottschal et al. [30], who did not observe a significant effect of inclination on spatiotemporal parameters.

Velocity 3.9–5 m/s

Four authors [34,35,41,42] conducted studies for velocities in this range. Padulo et al. [34,35], in both studies, measured the same parameters on the same inclinations: 0%, 2%, and 7%. Regardless of velocity, FT was the only parameter that shortened with each change in the inclination ($p < 0.05$). The difference in FT drop for the extreme inclination values for 3.9 m/s was close to 11%, and then increased to close to about 25% for 4.7 m/s [34]. SF grew with increasing inclination at 4.2 m/s [35], 4.7 m/s, and 5.0 m/s [34]. StL only noticed a decrease at 4.2 m/s. Of the length of 1.41 m, the StL was shortened by 0.03 m for an inclination of 2%, and by 0.06 m for an inclination of 7% ($p < 0.05$). SF and SL were investigated by Dickinson et al. [41], who saw a similar relationship for the inclinations of 0% and 5%. CT was similar for all gradient conditions at a given velocity. Depending on the velocity, the CT value oscillated between 160 and 180 ms. Padulo et al. [34,35], however, found no significant effect of gradient on CT. For the same parameter, different results were presented by Thomson et al. [42], who found statistically significant differences for all the inclinations tested ($p < 0.001$).

Table 3. Research characteristics and main results.

Study	Research Instruments	Performance	Parameter Tested	Inclination	Velocity	Comparing Conditions	Main Results
DeVita et al. (2008) [29]	Ramp with a length of 5 m and an incline of 10%, timing system (Brower Timing Systems, Model IRD-T175), the digital system consisting of eight cameras (Qualisys MacReflex240)	Participants dressed in athletic attire practiced running to adapt to the test conditions resulting from the speed limit. They then performed 5 trials for each incline.	SL	(−10%), 10%	3.35 m/s	(−10%) vs. 10%	During the run downhill, the stride length was 4% shorter compared to the run uphill ($p < 0.05$).
Gottschall and Kram (2005) [30]	Quinton 18-60 treadmill attached to the force platform, software LabView 4.0, National Instruments (Austin, TX, USA)	The protocol was preceded by a 10 min warm-up, with participants running downhill as well as uphill at a fixed inclination for one minute. Data were changed for the last 10 s of each trial.	SF, SL, CT, ST, DF	(−15.8%), (−10.5%), (−5.2%), 0% 5.2%, 10.5%, 15.8%	3 m/s	All inclinations vs. 0%	The spatiotemporal parameters were similar for each inclination. A significant increase in SF and DF and a decrease in SL were observed only for the largest inclination ($p < 0.05$).
Lemire et al. (2023) [31]	Treadmill (T-170-FMT, Arsalis, Belgium), MATLAB software version R2021a (MathWorks Inc., Natick, MA, USA)	Incremental test at 0%, starting at 8 km/h. Then, 3 randomized trials on (−17.6%), 0%, 17.6% inclination. The data were recorded continuously for 30 s (between 3:15 and 3:45 min/s) of each run at a constant velocity.	CT, AT, DF, SF, StL, RStL	(−17.6%), 0%, 17.6%	2.8 m/s	0% vs. (−17.6%) 17.6% vs. (−17.6%) 17.6% vs. 0%	CT was similar for each inclination. Significant increases in DF and decreases in AT ($p < 0.05$) were noted with each change in inclination. Significant differences for SF, StL, and RStL were noted only when the inclinations increased to 17.6% ($p < 0.05$). An increase in SF and a decrease in StL and RStL were observed.
Lussiana et al. (2015) [32]	Treadmill (Training Treadmill S1830; HEF Techmachine, Andrézieux-Bouthéon, France) Optojump photocell system (Micro Gate; Timing and Sport) Bolzano, Italy) sampling at 1000 Hz was placed adjacent to the treadmill	Two data collection sessions; subjects ran 7 × 5 min at 10 km/h using a self-selected SL and SF, thus completing a total of fourteen 5 min trials over 1 week. The seven 5 min trials included one trial at each of the following inclinations.	CT, FT, SF	(−8%), (−5%), (−2%), 0%, 2%, 5%, 8%	2.8 m/s	All possible combinations 0%, 2%, 5%, 8% with all negative inclinations, and (−5%) vs. (−8%) (−2%) vs. (−5%), (−2%) vs. (−8%)	CT was similar for each uphill run. Significant differences for FT ($p < 0.05$) were noted for (−2%) vs. (−8%) and each possible combination of 0%, 2%,5%, 8% vs. (−5%) and (−8%). A significant increase in SF ($p < 0.05$) was registered for (−5%) vs. (−8%), and all possible combinations of (−2%), 0%, 2%, 5%, 8% with (−5%) and (−8%). Only 5% and 8% were significantly different from the (−2%).
Lussiana et al. (2013) [33]	Treadmill (Training Treadmill S1830; HEF Techmachine, Andrézieux-Bouthéon, France) Optojump photocell system (Micro Gate; Timing and Sport) Bolzano, Italy) sampling at 1000 Hz was placed adjacent to the treadmill	Two data collection sessions; subjects ran 7 × 5 min at 10 km/h using a self-selected SL and SF, thus completing a total of fourteen 5 min trials over a 1-week period. The seven 5 min trials included one trial at each of the following inclinations.	CT, FT, SF	(−8%), (−5%), (−2%), 0%, 2%, 5%, 8%	2.8 m/s	All possible combinations 0%, 2%, 5%, 8% with all negative inclinations, and (−5%) vs. (−8%) (−2%) vs. (−5%), (−2%) vs. (−8%)	CT was similar for each uphill run. Significant differences for FT ($p < 0.05$) were noted for (−2%) vs. (−8%) and each possible combination of 0%, 2%,5%, 8% vs. (−5%) and (−8%). A significant increase in SF ($p < 0.05$) was registered for (−5%) vs. (−8%), and all possible combinations of (−2%), 0%, 2%, 5%, 8% with (−5%) and (−8%). Only 5% and 8% were significantly different from the (−2%).
Padulo et al. (2012) [34]	Treadmill (Run Race Technogym, Run 500; Gambettola, Italy), a high-speed digital camera, 210 Hz, Dartfish 5.5Pro software, kinematic data using a calibrated X-Pedar Mobile System (Novel GmbH (Munich, Germany))	The protocol included a 5 min run for each velocity, at all inclinations used.	StL, SF, FT, CT	0, 2%, 7%	3.9 m/s, 4.2 m/s, 4.4 m/s, 4.7 m/s, 5.0 m/s	0% vs. 2% 0% vs. 7% 2% vs. 7%	Significant FT shortening ($p < 0.05$) was noticeable for each inclination increase and in each velocity variant. The change in inclination resulted in an increase in SF and SL only at 4.7 m/s and 5 m/s ($p < 0.05$). No statistically significant changes were found for CT under any inclination or velocity conditions.

Table 3. *Cont.*

Study	Research Instruments	Performance	Parameter Tested	Inclination	Velocity	Comparing Conditions	Main Results
Padulo et al. (2013) [35]	Camera (Casio Exilim FH20), force platform (Model 9281A, Kistler AG, size 0.4 × 0.6 m)	The protocol included 5 min of running at a constant velocity, for all inclinations, with 5 min of passive rest.	StL, SF, FT, CT	0, 2%, 7%	4.2 m/s	0% vs. 2% 0% vs. 7% 2% vs. 7%	CT was similar for all inclinations. A significant decrease in FT ($p < 0.05$) was observed only for 0% vs. 7%. An increased SF and decreased SL were observed for each inclination increase ($p < 0.05$).
Padulo et al. (2023) [36]	Treadmill by Run Race 500; Technogym, optical device with 1000 Hz sampling frequency; OptoGait (Microgate, Bolzano, Italy)	10 min run in all inclines.	StL, SF, FT, CT	0%, 2%	IS: 4.3 ± 0.6 m/s	0% vs. 2%	Statistically significant changes were observed for stride frequency (SF), contact time (CT), and stride length (StL). With an increase in slope to 2%, SF increased, while StL and CT decreased ($p < 0.05$). No statistically significant differences were found for flight time (FT).
Park et al. (2019) [37]	Instrumented treadmill (Bertec Corp, Columbus, OH, USA, sampling frequency 1000Hz), 7-camera motion capture system (ProReflex MCU 240, Qualysis, Gothenburg, Sweden), software (Visual 3D, C-Motion, Germantown, MD, USA)	Participants ran at a constant velocity for 30 s, and the last ten successful steps were selected for analysis.	CT, ST, SL, SF	(−15.8%), (−10.5%), 0%	3.2 m/s	0% vs. (−10.5%) 0% vs. (−15.8%) (−10.5%) vs. (−15.8%)	Significant differences ($p < 0.05$) were observed between inclinations (−10.5%) vs. (−15.8%) only for CT. Other parameters, despite the evident change in inclination, were at similar levels.
Snyder et al. (2011) [38]	GRF platforms, (Labview 4.0, National Instruments, Austin, TX, USA), Matlab (The Mathworks, Natick, MA, USA)	7 min trails separated by 5 min rest on each incline with step frequency changes. For the first running trial, each subject ran without any instructions. Data were collected between 3 and 4 min for 30 s in each trial.	SF	(−5.2%), 0%, 5.2%	2.8 m/s	0% vs. (−5.2%), 0% vs. 5.2%, (−5.2%) vs. 5.2%	No significant relationship was noted between the different inclination conditions.
Telhan et al. (2010) [39]	10-camera motion capture system (model 624; Vicon Peak, Lake Forest, CA, USA) operating at 120 Hz. GRF synchronized with the motion capture data, LabVIEW (National Instruments Corp, Austin, TX, USA)	After 3 to 5 min of practice running on the instrumented treadmill, participants ran at 3.1 m/s on the treadmill, approximating an 8.5 min mile, on the following 3 surface slopes: 7% grade decline, 0%, and 7% incline.	SF, StL	(−7%), 0%, 7%	3.1 m/s	0% vs. (−7%), 0% vs. 7%	A significant increase in SF ($p < 0.05$) and decrease in SL ($p < 0.05$) were observed between incline running and level running. No significant differences were noted between incline running and level running.
García-Pinillos et al. (2019) [40]	Motorized treadmill (Salter M−835, Salter Int., Barcelona, Spain), OptoGait system	1 min of running at each inclination (30 s adaptation, 30 s recording).	CT, FT, SA, SF, StL	0%, 3%, 5%, 7%, 11%	3.3 m/s	All possible comparisons for the inclination used	Significant changes were observed for all measured parameters ($p < 0.05$). As the inclination increased, an SF increase and SL decrease were observed. CT increased markedly with the first change in slope, thus reaching the highest values for 3–7%. At the two final inclinations, it clearly shortened. FT and SA shortened up to a slope of 7% after which it began to increase.

Table 3. *Cont.*

Study	Research Instruments	Performance	Parameter Tested	Inclination	Velocity	Comparing Conditions	Main Results
Dickinson et al. (2020) [41]	Treadmill with adjustable incline angle and fixed measuring wheel by SpringCo Athletics (San Luis Obispo, CA, USA)	20 min of running at constant speed on a variable gradient. Parameters were measured at 5, 10, 15, and 20 min.	SF, SL	(−5%), 0%, 5%	4 m/s	Comparison of all possible inclination variants	SF and SL were similar for running at an incline of 0 and (−5%) ($p > 0.05$). With an increase in slope to 5%, there was a significant increase in SF and shortened SL ($p < 0.001$, ES = 0.70).
Thomson et al. (2021) [42]	AlterG® treadmill (G-trainer pro 2.0, AlterG®, California, USA, Loadsol®, pressure-sensing shoe insoles (Novel, Munich, Germany)	The trial time was 1 min, and data recording followed because of pre-adaptation to the running conditions. All possible trials resulting from the incline and speed of the run were performed.	CT	(−15%), (−10%), (−5%), 0%, 5%, 10%, 15%	3.3 m/s, 4.2 m/s	All possible comparisons for inclination and speeds of 3.3 and 4.2m/s	The results indicate ($p < 0.001$) a significant relationship between slope and CT. For negative gradients, the highest CT was recorded for (−5%) and the lowest for (-15%). For positive slope values, there was a linear increase in slope which peaked at 15%.
Zignoli et al. (2023) [43]	IMU (Inertial Measurement Unit), Movesense by Suunto (Finland), Optoelectronic system Optogait by Microgate (Bolzano, Italy)	10 min run on all inclinations and speed conditions.	SF, DF	(−8%), (−5%), (−2%), 2%,5%, 8%	80% PRS 90% PRS 100% PRS 110% PRS 120% PRS	All possible comparisons for inclination and speed	Statistically significant results were recorded only for the change in PRS velocity. For SF, a significant increase was observed between 80 and 120% PRS and 90 and 120% PRS ($p < 0.05$). DF decreased for each change in speed ($p < 0.001$).

SL (stride length), CT (contact time), ST (swing time), DF (duty factor), AT (aerial time), SF (step frequency), StL (step length), RStL (relative step length—% of height), SA (step angle), FT (flight time), PRS—individual’s self-selected preferred speed, IS (Individual Speed)—the average speed of the athlete’s best performance over a 10 km distance, reduced by 1 km/h.

Constant Individual Speed

Two authors used individually calculated velocities, based on each athlete's predisposition. Padulo et al. [36] determined this speed using the athletes' average lifetime record speed over a 10 km distance, which was 4.3 ± 0.6 m/s across all participants. Zignoli et al. [43] applied different speeds for selected runners, tailored to each athlete's preferred pace. Padulo et al. [36] observed statistically significant changes for three of the four parameters studied (StL, CT, SF). Despite a 2% inclination, he noted an increase in SF and a shortening of StL and CT. However, no significant changes in the spatiotemporal structure of the run under the influence of the gradient were observed by Zignoli et al. [43]. Although there was a wide range of gradients, SF and DF remained similar regardless of the degree of inclinations [43].

3.4.4. Changes in the Values of Selected Parameters

Bubble charts prepared in R Studio (version 4.3.3) illustrate quantitative changes for the most commonly analyzed parameters (SL, StL, ST, FT, CT, SF) (Figures 2–4) . The charts include studies that provide exact numerical results and assume a constant speed for all subjects [29–35,37–39]. For SL, the highest value, 2.48 m, was observed at a 0% incline [29]. The lowest value, 1.99 m, was recorded by Gottschall and Kram [30] at a 15.8% incline and a speed of 3 m/s. For StL, as for SL, the lowest value (0.99 m) was noted for a steep incline (17.6%) and a speed of 2.8 m/s. Padulo et al. [34,35] observed as much as a 71.7% (1.70 m) higher value on a 0% slope. This test was conducted at a much higher speed (5 m/s). For similar speeds, the numerical values of SL and StL were lower at high slope values (Figure 2).

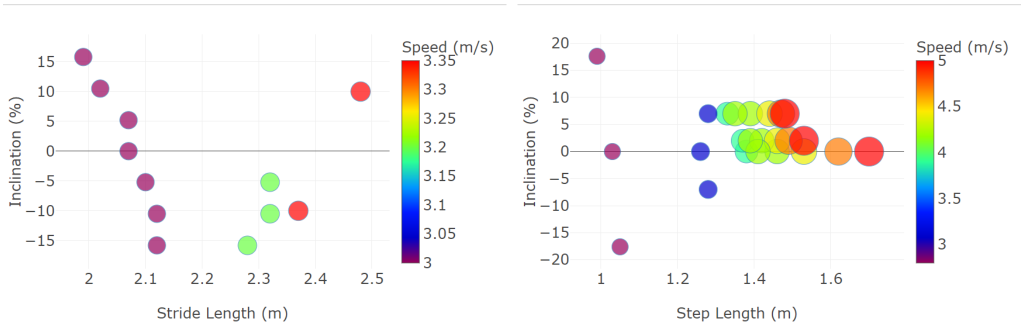

Figure 2. Bubble chart for stride length and step length.

The longest ST was observed for negative gradient values at low speeds. In all measured cases, however, it oscillated between 450 and 470 ms. The FT time lengthened with increasing speed and shortened with increasing slope [30]. In the study, FT decreased by 22% when the slope increased to 8% compared to −8% at a speed of 2.8 m/s. In the Padulo et al. study [34,35], the largest observed difference was 22.8% at a speed of 5 m/s (Figure 3).

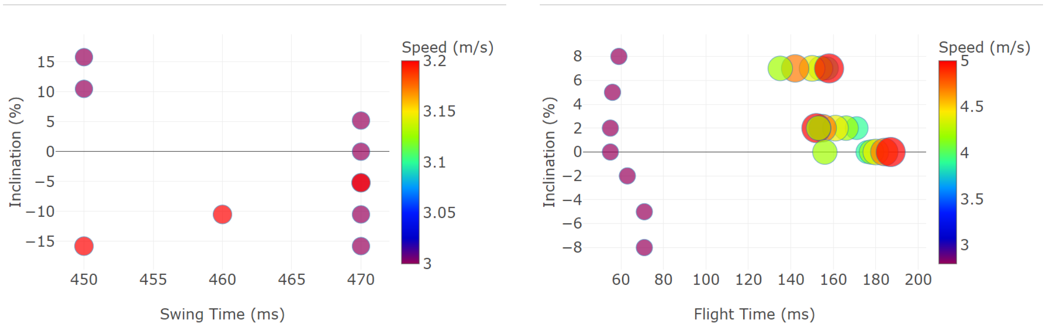

Figure 3. Bubble chart for swing time and flight time.

Step frequency increased with increasing slope. The largest percentage difference was noted by Padulo et al. [34,35], which was 14.58% (5 m/s, 0% to 7% slope). For the same inclinations, at 3.1 m/s, Telhan et al. [39] noted a difference of only 1.07%. CT values ranged from 250 ms to 330 ms for speeds of 2.8 to 3.2 m/s [30–33,37]. Significantly lower CT values were observed at high speeds (3.9–5 m/s), which ranged from 186 ms to 152 ms, according to Padulo et al. [34]. Regardless of inclinations, CT was slightly shorter at negative gradients and lower speeds [30,31]. For speeds of 3.9–5 m/s and inclinations of 0% to 7%, the differences became more pronounced as the speed increased. For a speed of 4.4 m/s, the increase in CT at a 7.19% versus a 0% gradient was 7% (Figure 4).

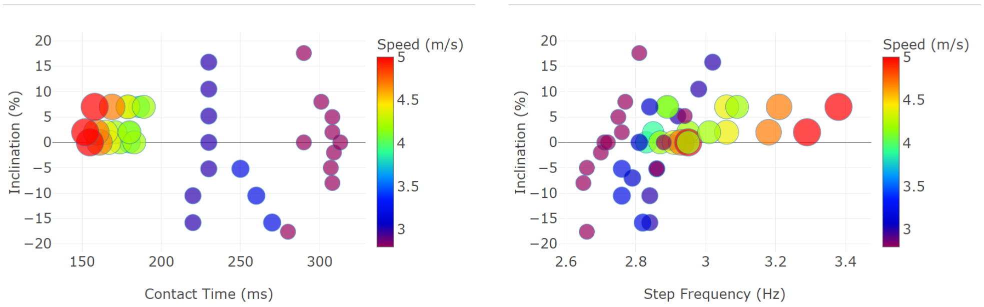

Figure 4. Bubble chart for contact time and step frequency.

4. Discussion

The current study aimed to provide an overview of the literature regarding the assessment of changes in spatiotemporal parameters under the influence of different inclinations. The study included downhill as well as uphill runs. The evaluation included studies in which a constant speed was used during the execution of the test. In the analysis of the results, the methods and research tools of the included papers were taken into account. The results of the review suggest that an increase in inclination changes the spatiotemporal structure of running. Parameters such as SL, FT, and SF changed most often and were characterized by exponential increases or decreases for positive inclination values. The results also indicated that the kinematics of running was different for downhill runs compared to uphill runs. Parameter values for negative values changed irregularly. CT was similar in all cases analyzed except for the three included studies [36,37,42].

Changes in spatiotemporal parameters were mainly determined by the inclination adopted in each study. Key to the analysis is a separate kinematic analysis for the uphill and downhill runs. All authors noted significant differences between inclinations and measured parameters, with the exception of Snyder et al. [38] and Zignoli et al. [43]. However, studies that included negative inclinations indicated that statistically significant changes most often involved positive values [30,31,39]. Lusianna et al. [32,33] noted significant differences for FT only for comparisons of running uphill versus running downhill. FT was unchanged for the inclines of −8% and −5%. Park et al. [37] investigated four parameters, considering only negative inclination values. He noted a significant decrease only for CT with an increase in the inclination from −15.8% to −10.5%. The different patterns of biomechanics for running at negative values may suggest the very direction of changes in the parameters studied. In all studies, the most common change observed was an increase in SF, with an increasing inclination, regardless of whether the studies included negative or only positive gradient values [30–36,39–41]. This development can be effectively used to optimize step frequency in the training process. Previous studies have shown that recreational runners are characterized by a lower cadence compared to athletes by about 10%. What is more, they choose a subjective selection of individual cadences that are lower by nearly 8% than their optimal step frequencies [44]. Properly selected training using inclinations could effectively increase the cadence of recreational runners, optimizing their technique and thus running economy.

Another trend has been presented by the FT. The value of this parameter in the study of Lussina et al. [32,33] significantly decreased during the run at 0% inclination, after which it began to increase once again. Moreover, the study by Lemire et al. [31] confirmed the same relationship for StL and RStL, which did not change significantly when the inclination increased from −17.6% to 0%.

Studies for positive inclination values, in some cases, also presented contradictory results. Garcia et al. [40] reported significant differences for CT or SA, but the values increased and decreased in a non-monotonic way. On the other hand, Gottschall et al. [30] described significant differences for SL, SF, CT, ST, and DF concerning the 0% inclination registered only for −15.8%. In other studies, Padulo et al. [34] reported no significant change in StL in one study, and in a second study, on the same gradients, observed a significant decrease in StL for each gradient [35]. It is worth noting that despite the divergence for SL, in both cases, an increase in SF was observed [34,35]. As for SF, the underruns could effectively optimize StL or SL. If stride frequency and step length are closely related [45], then appropriate selection of a positive slope could effectively optimize the length of a traffic jam relative to a given cadence. In the same way, rebound efficiency could be increased by reducing ground contact time. Maintaining a constant CT during uphill running could increase the quality of rebound during level running. Considering self-reported performance, maintaining an appropriate SF, SL, or StL would be key. For downhill runs, which are characterized by a longer flight phase [32,33] and the need for better shock absorption [46], this could, in turn, effectively improve the quality of the stabilizing phase of the running posture.

When analyzing spatiotemporal parameters under different inclination conditions, it is crucial to consider velocity in the context of the changes in the issue. Of the studies reviewed, excluding Padulo et al. [34–36,41,42], the authors evaluated velocities ranging from 2.8 to 3.35 m/s. Four articles evaluated the same speed (2.8 m/s) [31–33,38]. The results of the present study do not indicate a possible relationship between velocity and the direction of changes in individual parameters. Padulo et al. [34] observed a similar direction of change for SF even for extremely high velocities (4.7 m/s or 5 m/s). As reported in the previous literature [30–35,39,40], an exponential increase in SF with an increase in inclination was detected. However, speed can affect the amount of change for individual parameters. Research on different inclinations for multiple velocities has only been conducted by Padulo et al. [34] and Zignoli et al. [43] in terms of the FT difference between a 0% and a 7% slope, which showed a decrease in the speed of 5.0 m/s by 4.7% compared to 3.9 m/s. In contrast, for SF, a significant increase was observed only for velocities of 4.7 m/s and 5.0 m/s, which may also suggest an effect of velocity on the magnitude of changes in individual parameters [34]. Zignoli et al. [43], on the other hand, recorded no statistically significant differences in any of the parameters studied despite using five different speeds. He did, however, use individual speeds for each athlete, which may have influenced the results.

It is important to mention that the results may have also depended on the research tool, methods, and instruments used, and sample characteristics. In the included studies, there was variation in the duration of each trial. Garcia et al. [40] used 1 min of running at each incline, with 30 s of the participant adapting to the speed and 30 s of the participant adapting to the inclination. In some cases, the authors performed very long trials, up to 14 trials, with each trial lasting 5 min [32,33]. Regardless of the length of the trials in each study, the results presented similar values and the same direction of change for each parameter [29,32,33,35,39,40]. Overall, the results suggest that the trial time for moderate speeds does not cause excessive fatigue, which could disturb the spatiotemporal parameters of running.

The sample size and sex determination are also important elements to be considered, differentiating the included studies. The smallest sample sizes were identified in Padulo et al. [34] and Snyder et al. [38] and corresponded to eight (sex non-identified subjects) and nine men, respectively. However, it is difficult to discuss the effect of sample size on the results of the study, as Snyder et al. [38] found no relationship between them and Padulo et al. [34] showed significant changes for FT and SF. In contrast, the study by Padulo et al. [35] conducted a similar study at the same speed (4.2 m/s) and gradients (0%, 2%, 7%), and found significant statistical changes for SL in studies with a larger number of subjects of 18 participants.

Similar results were reported in a review article by Vernillo et al. [5] who performed a complex kinetic and kinematic analysis. Although there were differences in inclusion and exclusion criteria, the authors included some of the same articles of the current study [29,30,33–35,38,39]. The results mainly show an increased SF, shorter ST and AT, and similar CT for all inclinations [5]. However, the research conducted by Park et al. [37], which has stirred up a lot of controversy regarding the kinematics of downhill running, was not previously considered. Moreover, studies that contained analysis on inclinations greater than 20% were also included [47] as well as running individual velocity for each runner based on the athlete's aerobic abilities [9].

The current study has several limitations, which are related to the testing procedures used by the various authors. First, it is important to mention the different velocities and inclinations in the tests performed. Another distortion is the test execution time varied, which ranged from tens of seconds to tens of minutes. Despite the moderate velocity in all the included studies, prolonged exertion can cause fatigue and distortion of time and space parameters. Indeed, in a study by Yu et al. [48], a similar direction of change for SF was observed even for extremely high velocities (4.7 m/s or 5 m/s). Similar results were presented by Sheerin et al. [49], who also showed fatigue-induced changes in lower limb kinematics and kinetics. Hanley et al. [50], analyzing kinematic parameters during a 4 km race, also found that as distance and fatigue increased, a decrease in stride length, step frequency, and foot contact time was shown. Analyzing the results of the above authors, there is a risk that prolonged trials, even at moderate intensity, can alter running kinematics. Another factor that may have affected the reliability of the results was the use of different testing tools using different measurement technologies. Differences in spatiotemporal parameters can be small, so the use of different technologies could affect the results obtained. For the same reason, the sample size of 9–25 participants may be too small for reliable statistical analysis. In order to achieve the desired effect, the sample size should be larger and verified with statistical tools. Another factor limiting the objectivity of the study is the lack of genders in the results obtained. Some authors specified the number of males and females in the study group, but the results were ordered holistically, considering both sexes. The study by Henley et al. [50] observed significant differences for males and females in stride length and ground contact time. The differences for spatiotemporal parameters may be the result of significant differences in the biomechanics of the hip, knee, or ankle joint, which were noted in turn by Sinclair et al. [51]. In running with different inclinations, these differences could be just as noticeable, which significantly affects the results obtained.

Underestimation of the results may also have caused a moderate risk of bias, which amounted to 53.3% [30–35,39,41]. However, it is worth emphasizing that the ambiguities affecting the evaluation of the mentioned papers were due to the lack of specific information regarding the confounding factors in the study and not to methodological mistakes. The included studies were characterized by a refined strategy and, above all, a meticulously prepared research procedure. Therefore, the high percentage of risk of bias should not significantly affect the accuracy of the individual authors' results.

Even though the current study summarizes valuable information for coaches and practitioners on running kinematics. Some of the spatiotemporal parameters show wide variation depending on the inclination, velocity, or study procedure. Regarding some parameters, the authors do not agree on the direction of change in spatiotemporal parameters as determined by an increase or decrease in inclination. In addition, there is much controversy about the kinematics of running for negative gradient values, which is quite unpredictable in previous studies. Downhill runs at a more acute incline generate greater impact force, which can increase the risk of injury [30]. In addition, downhill runs require greater activation of the muscle group responsible for eccentric deceleration [52]. Increased muscle activity during downhill running indicates the body's natural ability to dampen and absorb shock resulting from the additional force of the foot hitting the ground [46]. The unpredictable change in step frequency during running may be related to the ability to manipulate it to reduce stress on the musculoskeletal system. The discrepancy in performance may depend on the experience and even the morphological predisposition of the groups tested. Perhaps what is needed is a comprehensive study with more gradients and opportunities to study muscle activity. The results of the review also indicate the need to analyze running at different velocities. Only three authors presented results for different running speeds [35,42,43].

Future research should also focus on the use of innovative technology to track kinetic and kinematic parameters in a comprehensive manner. Early studies in level running show that appropriate proportions of individual spatiotemporal parameters reduce the risk of injury as well as its effectiveness [13,45,53]. A holistic approach could explain in more detail to what extent the changes discussed affect the biomechanics of individual joints. The use of treadmills with pressure transducers and force platforms would, in turn, allow the evaluation of ground reaction forces. Comprehensive studies could explain in more detail the effects of individual running parameters on the entire musculoskeletal system. Analyzing the collected results and the differences for each parameter, the chosen technology should provide a high level of precision, allowing measurements with an accuracy of 1 cm and 1 ms. Gender differences observed in level running [50,51] also suggest that a study should contain separate analysis for females and males. Running kinematics are equally determined by steeper gradients and speeds that are close to 5 m/s and higher, which should be the focus of future research.

5. Conclusions

The overall results show high variability in terms of the research methods used. The lack of homogeneous conceptual assumptions in the included studies limits the definition of the effect of inclination on the spatiotemporal parameters of running. The heterogeneity of velocity, the magnitude of the gradient, and the very choice of spatiotemporal parameters are the main reasons that prevent a meta-analysis that could improve the present study with precise data. Although there is no detailed statistical analysis, the results indicate an increase in SF and a decrease in FT and SL with increasing inclination. Running uphill could therefore be incorporated into training to effectively optimize step frequency and step length. It would contribute to increased efficiency and economy among recreational runners. In order to better synchronize, coordinate, and thus reduce stress on the joints, it is worthwhile to train using runs with a higher step frequency. Maintaining a springy rebound and keeping a high step frequency on the runs could also improve the dynamics of the foot while running. The results also show little difference for individual inclinations. In several cases, statistically significant differences were seen only at the extreme conditions of the incline. Further studies need to be carried out with gradients exceeding 10% and, in particular, speeds of 4 m/s and above.

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