早稲田大学審査学位論文
博士（スポーツ科学）

Analysis of spatiotemporal variables in human running

ランニングにおける時空間的変数の解析

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博士学位論文概要

【第 1 章：緒言】

ランニングはヒトが成長するにつれて自然に習得する最も基本的な身体運動の 1 つである。走速度は空間的成分であるステップ長（1 歩の長さ）と時間的成分のケイデンス（単位時間当たりの歩数）の積によって決定される。これらの時空間的変数は走速度の変化にともなって相対的な貢献度が変化する事が知られている。低速度域ではケイデンスはほとんど増加せず、ステップ長の増加によって走速度が増加する。一方、高速度域になるにつれて、ステップ長の増加よりもケイデンスの増加によって走速度が増加していく。このような特性は、スプリンターや長距離選手のような陸上競技選手を対象にして報告されてきた。しかしながら、このような走速度の変化に伴う時空間的変数の相対的貢献度が、ランニングトレーニングや発育発達の影響を受けている可能性は否定できない。そこで、本学位論文では、ヒトのランニングにおける時空間的変数の調整について、トレーニングレベルや発育発達の側面から明らかにする事を目的とした。

【第 2 章:ランニングにおける時空間的変曲点:トレーニングレベルと競技モダリティの影響】

被験者はランニングに関する様々な背景を有する 80 名であった。被験者グループは短距離選手群、長距離選手群、陸上競技以外の様々な競技種目経験があるアスリート群、運動経験のないランニングに関する素人群の各 20 名で構成された。被験者は 30m（素人群のみ 20m）の直線路を様々な走速度で 20〜30 回走行した。この際のケイデンスとステップ長の値から、走速度-ケイデンス-ステップ長の関係（V - C - S 特性）が変化する“inflection point（変曲点）”についてデミング回帰を用いたセグメント化回帰法から算出した。その結果、変曲点走速度とステップ長が個々人の最大走速度と相関する事が明らかとなった。最大走速度(Vmax)はグループ間で有意に異なり、変曲点走速度はトレーニングレベル（特に陸上競技選手）に影響を受ける事が明らかとなった。しかしながら、変曲点におけるケイデンスや最大走速度からの相対的走速度はトレーニングレベルや競技モダリティの影響をほとんど受けないことが明らかとなった（変曲点ケイデンス：3.0 steps/s，相対走速度: 65-70%Vmax）。

【第 3 章：ランニングにおける時空間的変曲点：成長と発達の影響】

被験者は 1〜12 才の幼児・児童 46 名を対象とした。第 2 章の測定と同様に、4〜10m の直線路を複数回様々な走速度で走行することによって幼児・児童の V-C-S 特性を測定した。また、第 2 章で採用されたセグメント化回帰法を用いて、発育発達に伴う V-C-S 特性の変化と

inflection point の各変数について評価した。その結果、1〜6 才児で inflection point は算出されなかった。この年代の V-C-S 特性の特徴として、走速度の変化にともなうステップ長の変化が少なく、ケイデンスの増加によって走速度を増加させる傾向が得られた。これは、下肢筋力や筋腱のスティフネスが十分に発達していない事が要因として考えられる。一方で、9 〜12 才の児童の 80%以上に V-C-S 特性の inflection point が算出された。この事から、第 2 章で報告されてきた inflection point を有する V-C-S 特性は、特定の発育発達段階（第二次性徴）による身体的特徴の変化によって発現することが示唆された。

【第 4 章：幼児の接地パターンと疾走パフォーマンス】

第 2，3 章からトレーニングレベルや競技種目、発育発達段階が V-C-S 特性に特異的な影響を及ぼす事が明らかとなった。発育発達の影響が V-C-S 特性に与える影響をさらに詳細に評価するために疾走パフォーマンスを決定する指標の一つである接地パターンに着目した。本章では 3〜6 才の幼稚園児 282 名を被験者として、幼児の接地パターンと疾走パフォーマンスの関係を明らかにすることを目的とした。被験者は 25m 走路を 2 名ずつ並走して全力疾走した。その際の接地パターンと疾走パフォーマンスに関連する指標との関係について評価した。接地パターンは撮影された動画像から、踵接地（RF）、中足部接地（MF）、前足部接地（FF）に分類された。結果として、接地パターンの違いによる最大走速度の有意な差は見られなかった。接地時間は FF と MF が RF よりも有意に短く、成人で報告されている接地パターンと同様な結果が得られた。しかしながら、第 3 章の結果と同様に、幼稚園児では十分に身体機能が発達していないためステップ長を増加させる事が難しかったと考えられる。接地パターンの違いはケイデンスの差に関係する可能性があるが、成人よりも接地パターンが疾走パフォーマンスに及ぼす影響は少ない事が示唆された。

【第 5 章：総括論議】

トレーニングレベルや競技種目は個々人の最大走速度に影響を及ぼすが、変曲点のケイデンスや変曲点における最大走速度の相対的走速度に影響を及ぼさない事が明らかとなった。V-C-S 特性の決定には、機械的効率や代謝的効率が影響していることは先行研究からも確かである。本博士論文では効率について評価することはできないが、低速域と高速域では走速度に貢献する筋が異なることが先行研究で報告されており、変曲点は筋活動の神経制御が切り替わるタイミングと一致している可能性がある。成人における変曲点のケイデンス（3 steps/s）は共通していたため、ヒトのランニングにおける何らかの神経学的制御メカニズムが存在している可能性が示唆された。しかしながら、9〜12 才で変曲点が得られたことから、この神経制御は第二次性徴以降の身体的な変化が必要となることが示唆された。

ORIGINAL ARTICLE

This doctoral thesis is based on the following paper.

Spatiotemporal inflection points in human running: Effects of training level and athletic modality. **Yuta Goto**, Tetsuya Ogawa, Gaku Kakehata, Naoya Sazuka, Atsushi Okubo, Yoshihiro Wakita, Shigeo Iso, Kazuyuki Kanosue. PLoS One. 2021 Oct 18;16(10): e0258709. doi: 10.1371/journal.pone.0258709. eCollection 2021.

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Chapter 1 General Introduction

1-1 Research history of the Spatiotemporal parameters in human running

1-1-1 Spatiotemporal variables

Running is one of the most basic physical movements that human naturally acquire as they grow and develop. Running is expressed in different ways depending on the running velocity and the individual's level of effort, including "sprinting," which is running at maximum effort, and "jogging," which means running slowly. **Running velocity** is the product of **step length** and **step frequency**. Human running has been studied extensively from the viewpoint of how its temporal (step frequency) and spatial (step length) components contribute to velocity (Cavagna et al., 1988; Cavagna et al., 1991; Dillman, 1975; J. Hay, 2002; Hunter et al., 2004; Kaneko, 1990; Luhtanen & Komi, 1978; Nummela et al., 2007; Salo et al., 2011; Weyand et al., 2000). Step length is defined as the distance from foot contact to the following contact of the opposite foot, and step frequency is defined as the number of steps per unit time (Hunter et al., 2004). In addition, in studies on walking, step frequency is often expressed as **cadence** (Alton et al., 1998; Bilney et al., 2003; DeVita & Hortobagyi, 2000; Ishikawa et al., 2005; Tudor-Locke et al., 2011). The relative contribution of each component for changing running speed differs across the running speed range (Figure 1-1). A previous study reported that, at slower running velocity range, running velocity is modulated primarily by adjusting step length, whereas, at faster running velocity range, running velocity is modulated more by changes in cadence. Moreover, Hunter et al. (2004) reported that running velocities close to the maximum running velocity show negative interactions (increase in step frequency and decrease in step length). Some previous studies on sprinters and distance runners have suggested that the contribution of spatiotemporal variables to changes in running velocity switches around 7 m/s (Dorn et al., 2012; Luhtanen & Komi, 1978; Weyand et al., 2000). For sprinters, who are required to run faster and faster, it is important to determine how the contribution of step frequency and step length are determined. Hunter et al. (2004) explained the determinants of each parameter in the model shown in Figures 1-2 and 1-3, based on the "deterministic model" of Hay (1993). Negative interactions occur when a change in the elements associated with one spatiotemporal variable causes a negative effect on the elements associated with the other variable (e.g., an increase in step length and a decrease in step frequency due to an increase in flight time).

These relative contributions of spatiotemporal variables indicate the spontaneous recruitment of an adequate motor pattern that minimizes energy expenditure at a given running velocity (Cavagna et al., 1991; Minetti & Alexander, 1997; Salo et al., 2011;

Yanai & Hay, 2004). Mechanical approaches, such as Fenn's approach (Fenn, 1930a, 1930b), have been used as useful tools to elucidate these energy cost determinants with many practical applications (Peyre-Tartaruga et al., 2021). Yanai and Hay (2004), utilizing a two-dimensional simulation, evaluated the relative contribution of cadence and step length in the optimization of power production utilizing both anatomical (range of motion in the hip joint) and spatiotemporal (duration of the stance phase) determinants. Moreover, Cavagna et al. (1991) reported, measuring the aspects of mechanical efficiency, that the cadence is determined in the running velocity range between 13 and 22 km/h by exerted total power to maintain the movement of the center of gravity and accelerates the limbs relative to the center of gravity.

In addition, by measuring running economy (oxygen uptake per body weight), spatiotemporal adjustments between step frequency and step length have been reported in terms of metabolic efficiency. In these studies, running economy was assessed by measuring the economy when subjects ran at a freely chosen step frequency and a step frequency that was increased or decreased by several percent (Cavanagh & Williams, 1982; de Ruiter et al., 2014). It has been suggested that the cadence at which metabolic efficiency is optimal lies within a range of ±10% of the freely chosen step length (Cavanagh & Kram, 1989; Cavanagh & Williams, 1982; Connick & Li, 2014; de Ruiter et al., 2014; van Oeveren et al., 2017) .

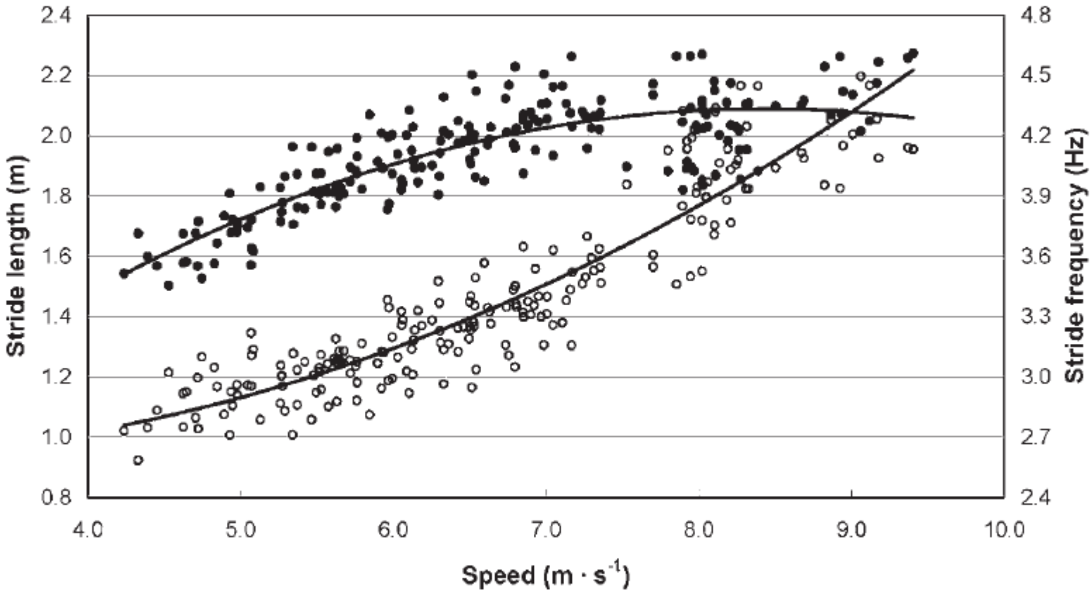

Figure 1-1. Relationship between step length and step frequency in response to changes in running speed (adopted from Nummela et al., 2007).

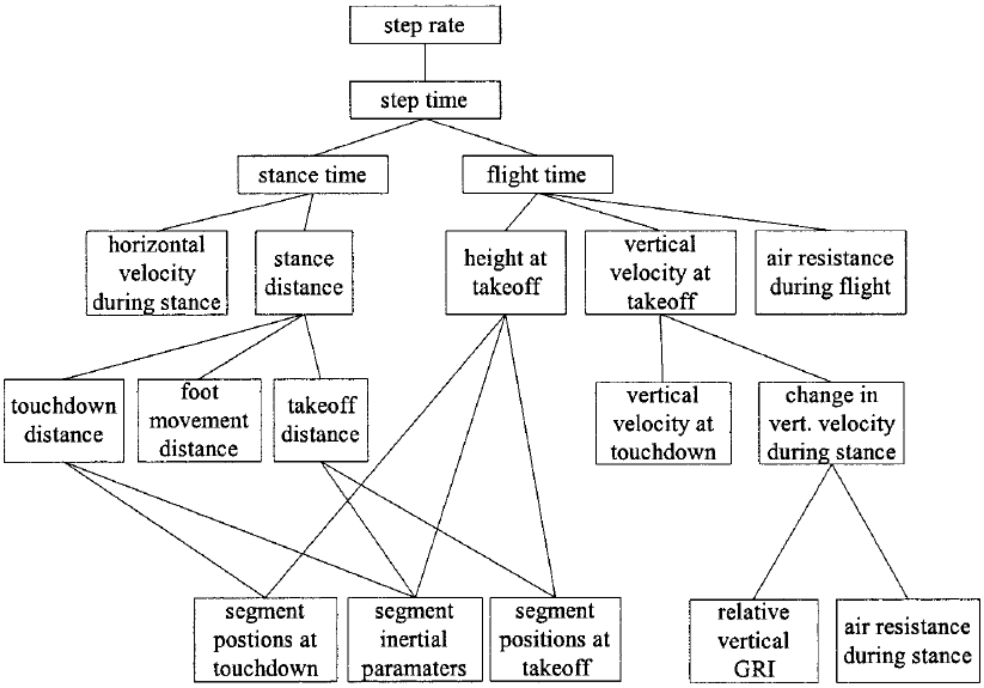

Figure 1-2. Determinants of step rate adapted from Hay, 1994 (from Hunter et al., 2004)

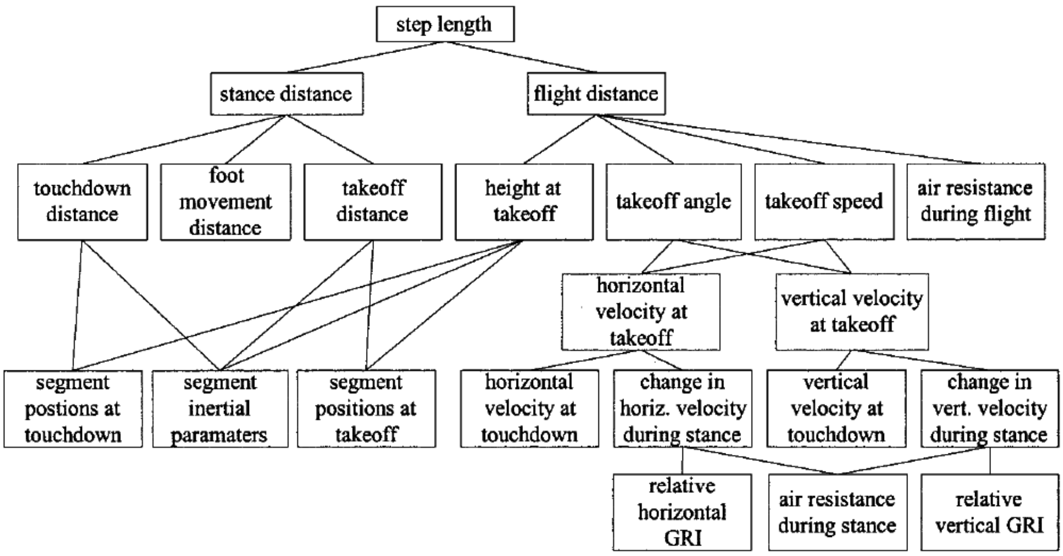

Figure 1-3. Determinants of step length adapted from Hay, 1994 (from Hunter et al., 2004)

1-1-2 Acquisition and development of running motor characteristics

Humans naturally acquire individual running movements with their growth and development, and the acquisition of this running movement takes several stages to maturity (宮丸, 2001). A study that revealed the change in cadence and step length during sprinting with development reported that cadence showed almost constant values from 2 to 12 years of age regardless of age (斉藤 & 伊藤, 1995). In addition, a longitudinal study of the development of sprint ability in boys and girls aged 7 to12 years showed an increase in sprinting velocity across all ages except 9 to10 years, with a step length of 7 to12 years old showed an increase between all ages (宮丸, 2001). Furthermore, in 12 to 14 years old children, it has been reported that the factor of change in running velocity of sprinting was not an increase in cadence but step length. Namely, the increase in running velocity of sprinting from 1 to 14 years old is more influenced by the increase in step length than the cadence. However, the increase in the running velocity of sprinting due to growth and development is not always achieved by efficient running movement. 宮丸 (2001) reported that children with a faster running velocity of sprinting in the first grade of elementary school tended to be faster in the sixth grade of elementary school and vice versa. It has also been suggested that childhood sprinting ability levels may not improve unless special training is given (信岡 et al., 2015). In other words, there are individual differences in the running movements that are formed with the developmental stage. The running movement ability acquired by around 6 years old may influence the subsequent running performance if some training is not performed to improve their running movement. Comprehensive clarification of how running ability develops by this age is considered necessary for the deep understanding of the formation of running ability.

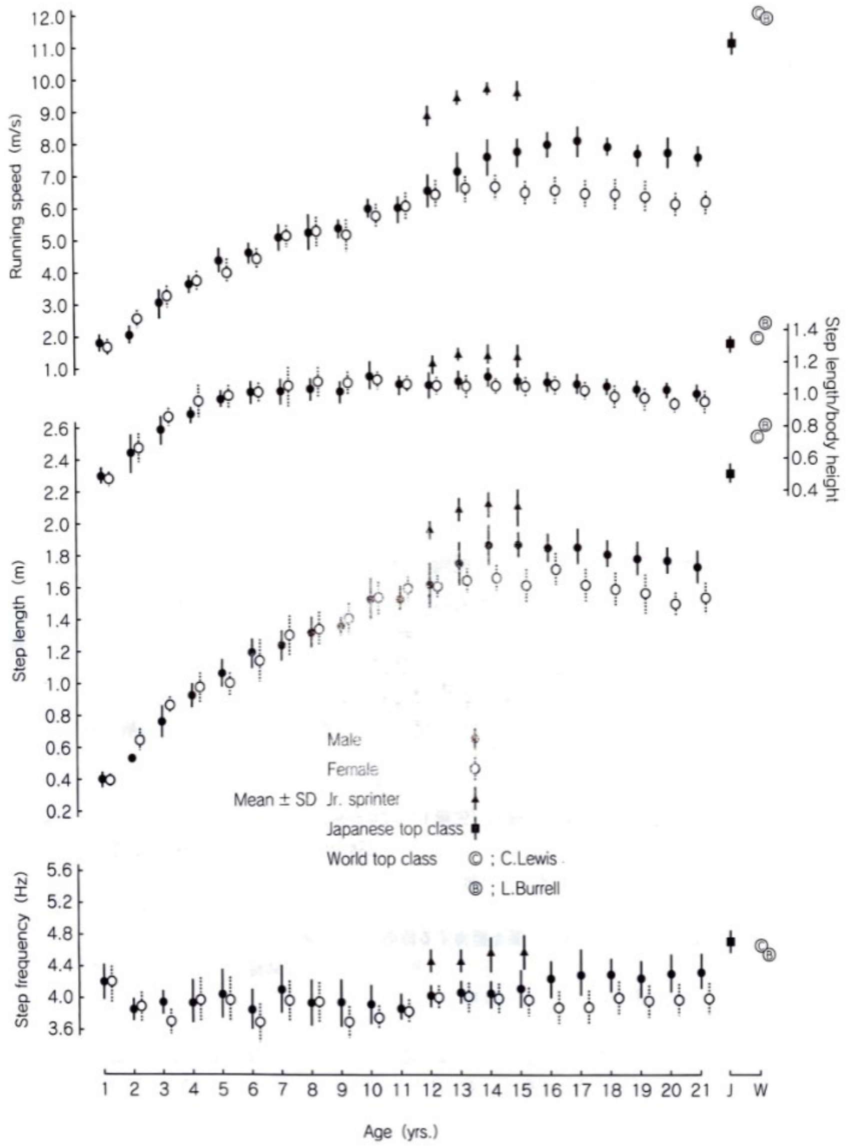

Figure 1-4. Changes in maximal running speed, step length, step length/body height, and step frequency with age (宮丸, 2001)

There are many studies on the ability to run at full velocity in early childhood, but few studies have measured the basic characteristics of running velocity, step length and cadence in a wide velocity range in relation to development (Schepens et al., 1998; Schepens et al., 2001). This characteristic is expected to change with aging, but the relationship between this running velocity-cadence-step length relationship and sprinting ability in developing children is unknown. If there is a specific difference in this characteristic at a certain stage of development, it would become an important knowledge for the training to improving sprinting ability in children.

1-2 Research on foot strike pattern

The foot strike pattern (Figure 1-5) is one of the indices to evaluate the running movement of an individual in the running. The identification of the foot strike pattern is determined by the first contact point of the foot on the ground. The foot strike pattern can be classified into three patterns: a **rearfoot strike pattern (RF)**, in which the heel first contacts the ground; a **midfoot strike pattern (MF)**, in which the heel and the metatarsal head contact the ground simultaneously; and a **forefoot strike pattern (FF)**, in which the metatarsal head or the ball of the thumb first contacts the ground before or without the heel contact the ground (Altman & Davis, 2012; Forrester & Townend, 2015; Lieberman et al., 2010). In a study that measured the foot strike pattern of adult male and female runners with their shoes on, it was reported that as running velocity increased, the foot strike pattern of most runners changed from a rearfoot strike pattern to a midfoot strike pattern or forefoot strike pattern (Breine et al., 2014; Keller et al., 1996). This may be because the midfoot/forefoot strike pattern contributes to an increase in running velocity in the faster velocity range.

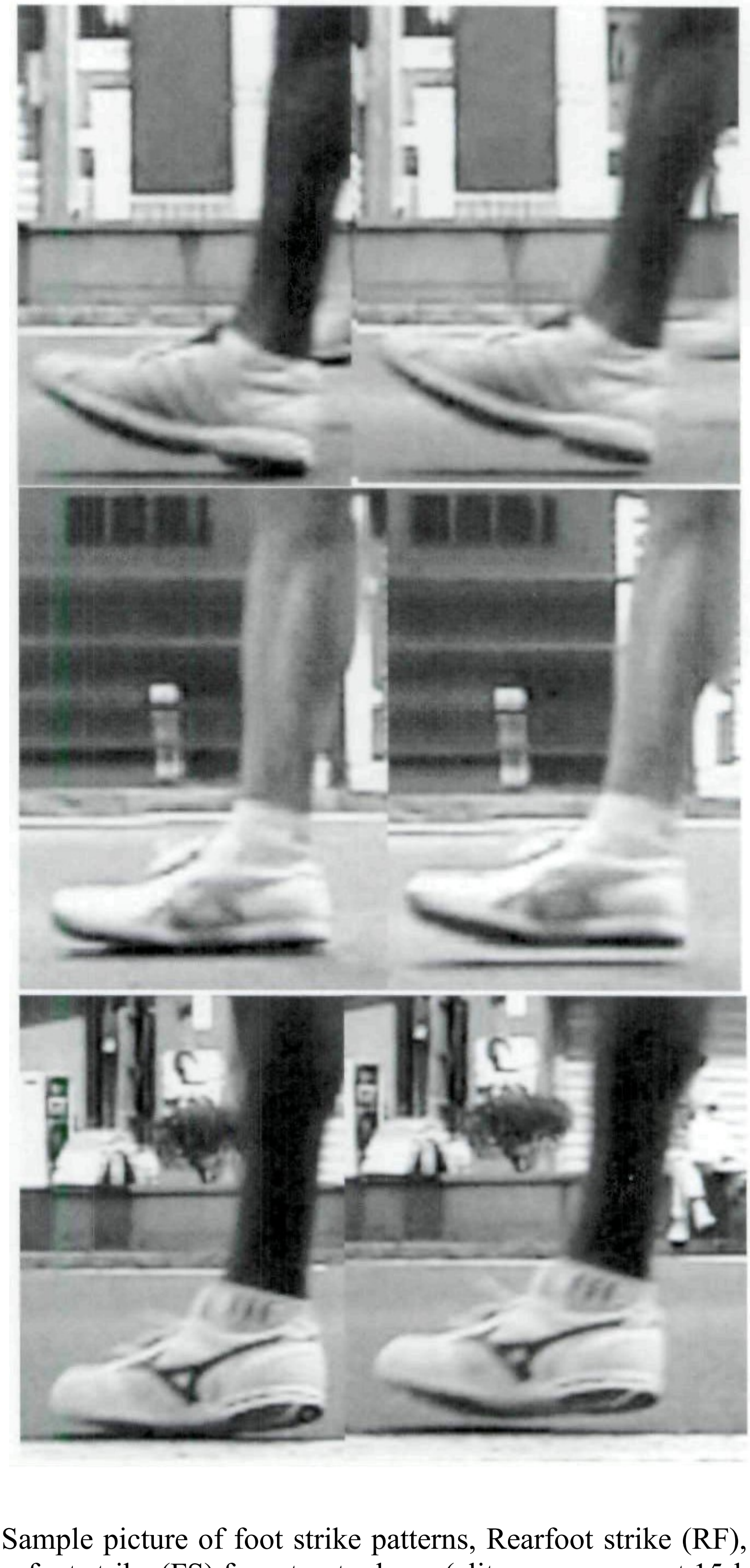

Figure 1-5. Sample picture of foot strike patterns, Rearfoot strike (RF), midfoot strike (MF), and forefoot strike (FS) from top to down (elite men runner at 15-km point of half marathon). (adapted from Hasegawa et al. (2007))

Indeed a previous study comparing ground reaction forces during running motion between foot strike patterns reported that the rearfoot strike pattern transmitted a greater vertical ground reaction force to the foot immediately after ground contact than the forefoot strike pattern (Payne, 1983). It is also possible that cushioned shoes and well-prepared ground allow for heel-ground contact during running at faster running velocities (B. M. Nigg, 1997). Studies in adults have shown that rearfoot strike pattern runners in shoes tended to have midfoot or forefoot strike patterns when running barefoot or on hard ground without the cushioning effect of shoes (Gruber et al., 2013; Lieberman et al., 2010). In other words, environmental factors also influence the foot strike patterns.

Reports on foot strike patterns in children are scarce, and the relationship between development and foot strike patterns is still unclear. 信岡 et al. (2020) clarified the actual state of foot strike patterns in children and the relationship between foot strike patterns and sprinting performance. The proportions of midfoot and forefoot strike pattern children in elementary schools are lower than those in adults, reporting that the foot strike pattern could be influenced by factors such as physical development.

However, it is still unclear whether these characteristics would be applied to even preschool children (2 to 6 years). Investigating the foot strike pattern formation process in young children, in relation to the stage of acquiring the basic running form (Miyamaru,1995), is expected to help improve their running performance in their childhood.

1-3 The purpose of this thesis

Many studies have analyzed the adjustment of spatiotemporal variables in athletics and well-trained active athletes. However, the extent to which the spatiotemporal adjustment occurs in different populations and persons with different physical backgrounds remains unclear. In addition, clarifying how these characteristics are formed during growth and development may provide useful insights for improving running performance in childhood. Therefore, to provide new insights into running research and training, it is necessary to consider people with different backgrounds in the running.

The purpose of this doctoral thesis is to clarify how changes in running velocity alter the spatiotemporal coordination of stride length and cadence in subjects from different backgrounds, and its change with development in children.

In **Chapter 2**, I obtained spatiotemporal adjustment between step length and cadence in a wide range of running velocity from the minimum to the maximum in subjects with different histories of engagement in running training. I calculated the critical point ("inflection point") that changes the relative contribution between cadence and step length. Moreover, I also investigated how this inflection point relates to running training.

In **Chapter 3**, to analyze how the running characteristics observed in adults are developed, I investigated the spatiotemporal adjustment of running in 46 children ranging from 1 to 12 years.

In **Chapter 4**, I clarified the relationship between foot strike patterns and sprint performance in preschool children ranging from 3 to 6 years.

In **Chapter 5**, the general discussion was made from the results of Chapters 2, 3, and 4.

In **Chapter 6**, I presented the conclusion of this study.

Chapter 2

Spatiotemporal inflection points in human running: effects of training level and athletic modality. (Based on Goto et al., (2021) PLOS ONE.)

2-1 Introduction

Running velocity equals the product of cadence and step length, and the relative contribution of each component to changing velocity differs across the running velocity range. A previous study reported that, at slower velocities, running velocity is modulated primarily by adjusting step length, whereas, at faster velocities, running velocity is modulated more by changes in cadence. However, the extent to which the above characteristics occur in different populations and in persons with different physical backgrounds remains unclear. Most of the above-mentioned studies focused on well-trained individuals, especially those trained for running (Dorn et al., 2012; Hunter et al., 2004; Nummela et al., 2007; Weyand et al., 2000; Yanai & Hay, 2004).

Therefore, the purpose of the present study was to investigate how a change in running velocity altered the spatiotemporal adjustment between step length and cadence in subjects with different histories of engagement in running training. Namely, we studied:1. sprinters, 2. distance runners, 3. active athletes who had received no running-specific training, and 4. sedentary, untrained subjects. The relationships among running velocity, cadence, and step length over a wide range of running velocities were compared across these subjects. Among the four groups, the distance runners would be expected to run as efficiently (either mechanically or metabolically) as possible. As noted above, in the slower velocity ranges, altering step length is a more energy saving strategy for changing velocity than is altering cadence (Yanai & Hay, 2004). Therefore, we hypothesized: 1. the running step length/cadence patterns of individuals would be influenced by their running training experience and overall physical activity levels and 2. distance runners would exhibit the greatest tendency to change velocity by altering step length in the slower velocity range.

2-2 Methods

Subjects

A total of eighty volunteers (69 males and 11 females) with different backgrounds, in terms of their running experience, participated in the study. They were assigned into one of four groups depending on their current/previous running training. We utilized four groups of subjects with different histories of running training. The first and second groups consisted of twenty sprinters (all men) and twenty distance runners (all men), respectively. The participants in the third group were twenty active athletes (16 males and 4 females). Although running is involved in many of the sports, all subjects informed us that they had received no special training for improving their running velocity. For reference, the sports that the participants in the third group engaged in were: soccer, basketball, softball, weightlifting, boxing, lacrosse, volleyball, American football, badminton, handball, rowing, judo, and golf. They had all participated in their sport for at least 5 years. The fourth group consisted of sedentary individuals without a history of any regular participation in sports activities (13 males and 7 females). Table 2-1 lists the characteristics of participants in each group. All participants were informed of the purposes and procedures, and signed an informed consent form. This study was approved by the Human Research Ethics Committee in Faculty of Sport Sciences, Waseda University. The experiments were conducted in accordance with the Declaration of Helsinki.

Table 2-1. Physical characteristics and sport activity history of each subject group.

	N	age, years	height, cm	sports activity history, years
Sprinters	20	22 ± 2	176.2 ± 6.1$^{b, c, d}$	9.7 ± 3.0
Distance runners	20	20 ± 1	171.0 ± 4.5	7.4 ± 2.0
Active athletes	20	23 ± 2	170.1 ± 5.8	10.2 ± 4.4
Sedentary individuals	17	22 ± 2	166.0 ± 6.2	

Values are means ± SD. N, number of subjects. b, c, d: values are significantly different from distance runners, active athletes, and sedentary individuals, respectively ($p < 0.05$). The sport activity history of the active athletes indicates the number of years of participation in that sport for each subject.

Experimental setup and tasks

Experiments were conducted on a 30 m all-weather straight track (only 20 m for the sedentary group in consideration of their physical strength and lack of stamina) on which color markers were placed every 0.5 m for video analysis. A sagittal view of each participant was recorded by panning with a video camera (HDR-CX630V, SONY) placed approximately 10 m lateral to the center of the running path. An additional 10-30 meters was provided before and after the filming zone (of 30m or 20m) so that the subjects could accelerate and decelerate and thus maintain running velocity as constant as possible throughout the recording area. This acceleration distance differed between trials and was selected by the subject. The video sampling frequency was 60 Hz.

Participants were asked to run along the path 30 times at a variety of velocities, which varied from slow to the fastest possible. The order of running with different velocities was randomized on a subject-by-subject basis. The subjects were directed to run at a particular percentage of their maximal effort (Kakehata et al., 2020). This instruction included requesting a subjective effort from 10% to 100% of maximum, as well as “run faster or slower than the previous trial”. The actual running velocity did not necessarily match the exact percentage of their maximal velocity. However, this method did produce the necessary array of running velocities and the subjects might run more than once at an intensity. When running at the minimum velocity, subjects followed our instruction to run as slowly as they could while still maintaining a running gait (as opposed to walking, jumping, hopping, or bounding). The interval between trials ranged from 30 seconds to 5 minutes, depending on the velocity of the previous trial. A 5-minute rest was taken after 15 trials. The participants used their own running shoes. Spiked shoes were not allowed.

Data analysis

Offline data analysis was performed by using video administration software (PlayMemories, SONY, Japan). On the basis of the video analysis, the running velocity, cadence, and step length were calculated on a trial-by-trial basis for each subject. Mean running velocity (m/sec) was calculated by dividing the length of the path (m) by the time taken (sec) to run over the path. The instant at which the subject passed the start and the end point were identified from the position of the chest relative to the color markers. Mean cadence (steps/sec) was calculated by dividing the number of steps by the time taken to cover that distance. The number of steps was counted from the first ground contact with the path to the last ground contact before passing the end point. The duration utilized was defined as the time between the instant of first foot-contact after the start position and that of the last foot-contact before the end. Mean step length (m) was calculated by dividing the mean running velocity (m/sec) by the mean cadence (steps/sec). Step length was also expressed as the ratio of the step length (m) to the height (m) of each subject in order to examine the influence of the physical characteristics of the subjects. For the running velocity, the fastest among the 30 trials by each subject was designated as their maximal running velocity.

In the present study, the principal analyses for the spatiotemporal running characteristics of each subject were performed with MATLAB version R2018a (The

MathWorks, Inc., USA). For each subject, the data were plotted as shown in Figure 2-1 in order to examine the relationship between cadence and step length (horizontal axis: cadence, vertical axis: step length). This correspondence involved the Velocity (m/s, dotted line), Cadence (steps/s, horizontal), and Step length (m, vertical), and is defined as the **V-C-S relationship**. To quantitatively analyze the critical point at which the relative contribution of spatiotemporal adjustment changed (cadence vs. step length), we utilized the segmented regression method which has previously been used to detect lactate threshold (Ivy et al., 1980) and ventilation threshold (Neder & Stein, 2006) during aerobic exercise. This is a statistical method for determining the point at which a line suddenly changes slope at some unknown point. We used a segmented regression procedure (Chen et al., 2011; Neder & Stein, 2006) in which the N data points were divided into two segments (the lower x data and the upper N-x data, x = 3, 4, …, or N-2). Each segment was fitted with a regression line using the Deming regression (Deming, 1943; Martin, 2000). This regression method was adopted to exclude the effects of measurement errors in cadence and step length. That is, one regression line was obtained with x data points from the ascending order starting with the minimum velocity, and the other one with N-x data points from the descending order starting with the maximum velocity. The critical point ("inflection point"), then, was the intersection of the two regression lines with an x value that minimized orthogonal distance between measurement data and regression line for two data sets (segments) (Fig. 2-1, cross; X). We assumed that the regression lines below and above the inflection point would adequately represent the spatiotemporal characteristics of running for each subject and group.

Subjects with inflection points, thus obtained, that differed largely from the measured points, were excluded from the analysis (#18, #19, and #20, as seen in Figure 2-8). Therefore, the final analysis involved 20 sprinters, 20 distance runners, 20 active athletes, and 17 sedentary individuals. For these subjects, running velocity, cadence, and step length at the inflection point were calculated. Normalized values were determined for each parameter at the maximal running velocity.

Statistical analysis

Statistical analysis was performed using SPSS Statistics 23 software (IBM, USA). Maximal running velocity, height of subjects, and all variables related to inflection point in each group were tested for a normal distribution using the Shapiro-Wilk test. Maximal running velocity, height, and normalized cadence at the inflection point were found to have non-normal distributions. Thus, group mean data for maximal running velocity, height of subjects, and all variables related to inflection point were analyzed among the four subject groups by using a non-parametric Kruskal-Wallis test. Next, post-hoc pairwise comparisons using the Dunn-Bonferroni approach were made to identify additional differences between the groups. In order to further investigate the possible mechanisms responsible for the inflection point, correlational analyses were performed.

All variables across all subjects related to the inflection point and maximal running velocity were tested for a normal distribution using the Shapiro-Wilk test. Maximum running velocity, and step length at maximal running velocity exhibited normal distributions. Likewise, running velocity (both unnormalized and normalized), step length (both unnormalized and normalized), and unnormalized cadence at the inflection point exhibited normal distributions. However, cadence at maximal running velocity and normalized cadence at the inflection point exhibited non-normal distributions. Pearson’s and Spearman's correlations were performed to analyze the relationship between maximal running velocity and other parameters at the inflection point. Significance was set at $p < 0.05$. The data are presented as mean and standard deviation (mean ± SD).

2-3 Results

Figure 2-1 shows a typical example of the relationship between running velocity, cadence, and step length for a single sprinter. Both cadence and step length show specific changes in relation to changing running velocity. The inflection point (cadence: 2.97 steps/s, step length: 1.78 m) was computed from two regression lines.

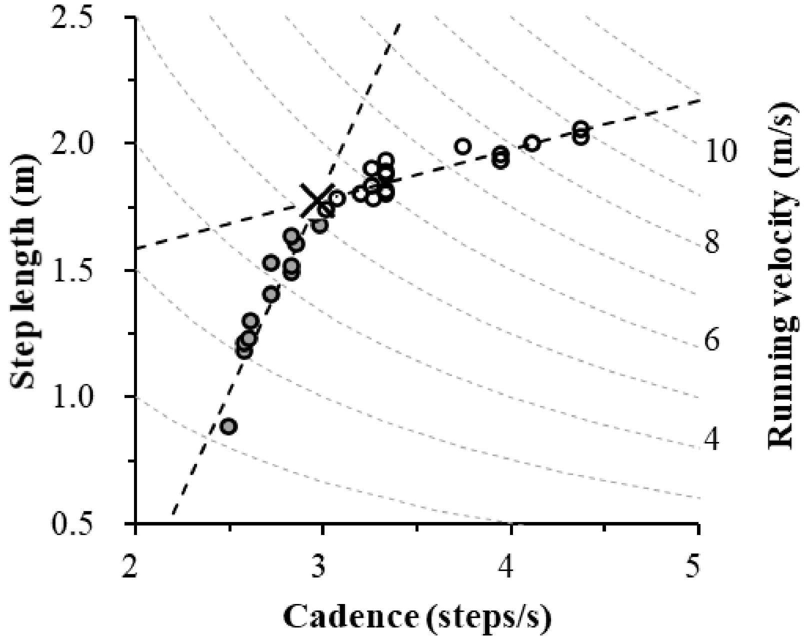

Figure 2-1. The relationship between cadence (steps/s, horizontal) and step length (m, vertical) relative to running velocity (pale broken line and the second vertical axis) in a single sprinter. The inflection point (cross) was computed from two regression lines from different data sets by combining the segmented regression method of Deming regression. The filled and open circle markers represent the data sets below and above the inflection point at which the relationship between cadence and step length changed abruptly. Inflection point was obtained as the intersection point of the two regression lines.

Figure 2-2A shows an inter-group comparison of the mean values of Vmax. A Kruskal-Wallis test revealed significant differences between the groups in terms of maximum running velocity ($\chi2$ (3) = 52.463, $p < 0.001$). The post-hoc comparisons revealed that the maximal velocity of the sprinters was faster compared to all the other subject groups (distance runner: $p = 0.009$, active athlete: $p < 0.001$, sedentary: $p < 0.001$). The distance runner group exhibited significantly faster maximal running velocity in comparison with the sedentary individual group. Figure 2-2B-D illustrates the correlation between maximal running velocity and cadence, absolute step length and step length normalized to height at the maximal running velocity. There were significant positive correlations between Vmax and cadence as well as step length both in the unnormalized and normalized forms (cadence: $r = 0.514$, $p < 0.001$; step length (unnormalized): $r = 0.843$, $p < 0.001$; step length (normalized): $r = 0.803$, $p < 0.001$).

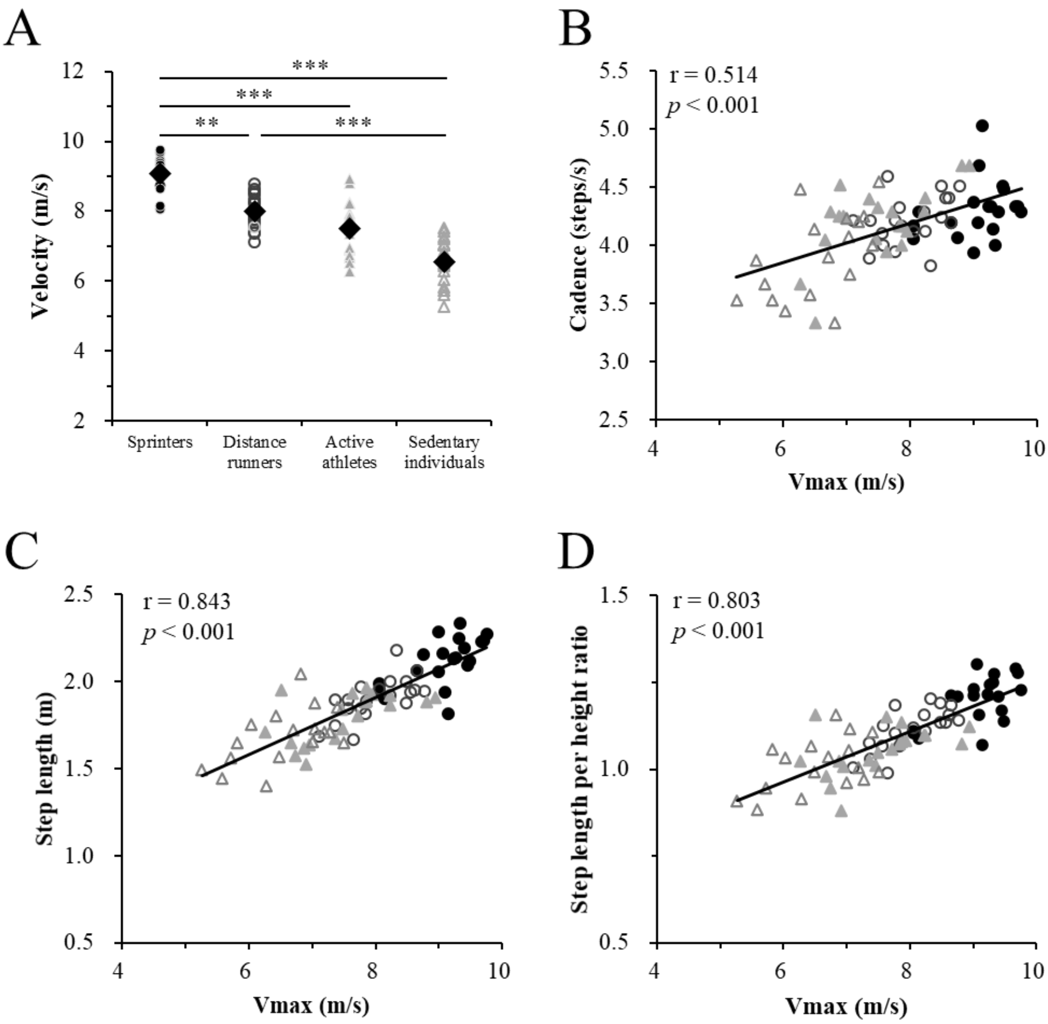

Figure 2-2. Inter-group comparison of mean values (diamond) of the maximum running velocity (Vmax) (A), and correlation between the maximal running velocity and the cadence (B), step length (C), and step length normalized by height (D) at maximal running velocity. In Figure 2A, open circles indicate each individual subject. Significant difference; ***p < 0.001, **p < 0.01. In Figure 2B-D, filled circles, open circles, filled triangles, and open triangles represent the sprinters, distance runners, active athletes, and sedentary individuals, respectively. There are significant positive correlations between Vmax and the cadence (B) and between Vmax and step length, both absolute velocity and velocity normalized to maximal running velocity (r = 0.514, p < 0.001; r = 0.843, p < 0.001; r = 0.803, p < 0.001, respectively).

Figure 2-3A shows mean values of cadence and step length at maximal running velocity (Vmax), the inflection point, and minimal running velocity (Vmin) for each subject group.

As shown in Figure 2-3A, maximal running velocity was different across the groups and was the fastest in the sprinters (around 10 m/s) and slowest in the sedentary individuals (mostly less than 8 m/s). All groups tended to increase step length predominately at the velocities between Vmin (velocity: 2.17 ± 0.45 m/s, cadence: 2.62 ± 0.14 steps/s, step length: 0.82 ± 0.17 m) and the inflection point, and then to increase cadence until they reached Vmax. Figure 2-3B depicts mean values of cadence and step length normalized to the values obtained under maximal running velocity. The characteristics of the increase in velocity were similar to those from Figure 2-3A. Due to differences in the absolute value (Figure 2-3A) of maximal running velocity, the normalized cadence varied considerably across the subject groups, while variability in step length below the inflection point was less evident.

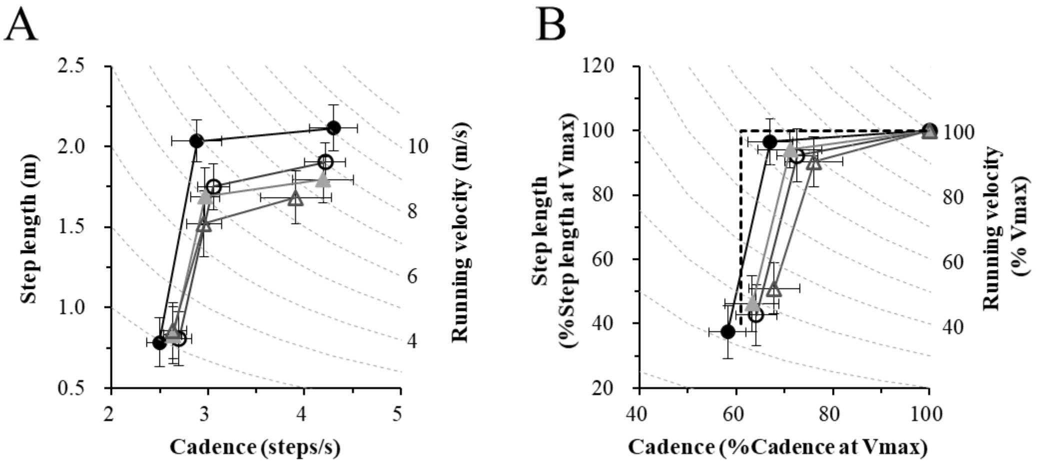

Figure 2-3. Mean values of cadence and step length at the maximal running velocity (Vmax), inflection point (IP), and minimal running velocity (Vmin) (A), and those with cadence and step length normalized to those under Vmax (B) for each subject group. The error bars depict the standard deviation. The filled circles, open circles, filled triangles, and open triangles represent sprinters, distance runners, active athletes and sedentary individuals, respectively. Pale broken lines represent running velocity (A) and running velocity normalized by maximal running velocity (B). The thick broken line in B illustrates the limiting situation, in which velocity change is only done with a step length change in the velocity range below the inflection point, and only with a cadence change above the inflection point.

Table 2-2 Kinematic variables at the inflection point.

	Sprinters (N = 20)	Distance runners (N = 20)	Active athletes (N = 20)	Sedentary individuals (N = 17)
velocity, m/s	5.86 ± 0.59 $^{c, d}$	5.36 ± 0.60 ^{d}	5.00 ± 0.50	4.50 ± 0.65
step length, m	2.03 ± 0.13 $^{b, c, d}$	1.75 ± 0.14 ^{d}	1.69 ± 0.18	1.52 ± 0.21
cadence, steps/s	2.88 ± 0.26	3.06 ± 0.17	2.97 ± 0.15	2.96 ± 0.18
normalized velocity, %	64.7 ± 7.1	67.0 ± 7.5	66.7 ± 4.8	68.6 ± 7.4
normalized step length, %	96.5 ± 7.2	92.2 ± 8.2	94.1 ± 5.8	90.3 ± 7.7
normalized cadence, %	67.0 ± 4.7 $^{b, d}$	72.6 ± 4.2	71.2 ± 6.6	76.0 ± 6.0

Values are means ± SD. N, number of subjects. b, c, d: values are significantly larger, from distance runners, active athletes, and sedentary individuals, respectively. Normalized velocity, step length, and cadence were obtained by normalizing with corresponding values at the maximal running velocity, respectively.

Table 2-2 shows inter-group comparison of the mean values of all variables related to the inflection point. A Kruskal-Wallis test revealed significant difference of running velocity, step length, normalized cadence (χ^2 (3) = 31.215, $p < 0.001$; χ^2 (3) = 42.68, $p < 0.001$; χ^2 (3) = 23.623, $p < 0.001$, respectively). The post-hoc comparisons revealed significant differences between the subject groups. In the group of sprinters, the running velocity was significantly faster as compared to the active athlete, and sedentary subject groups (active athlete: $p < 0.01$, sedentary: $p < 0.001$). For the same parameter, the group of distance runners showed significantly faster in comparison to the sedentary group ($p < 0.01$). The step length was significantly longer in the sprinter group in comparison to all the other subject groups (distance runner: $p < 0.01$, active athletes: $p < 0.001$, sedentary: $p < 0.001$). For the same parameter, the group of distance runners was significantly longer than the sedentary group ($p < 0.05$). In the group of sprinters, the normalized cadence was lower as compared to distance runner and sedentary subject groups (distance runner: $p < 0.01$, sedentary: $p < 0.001$).

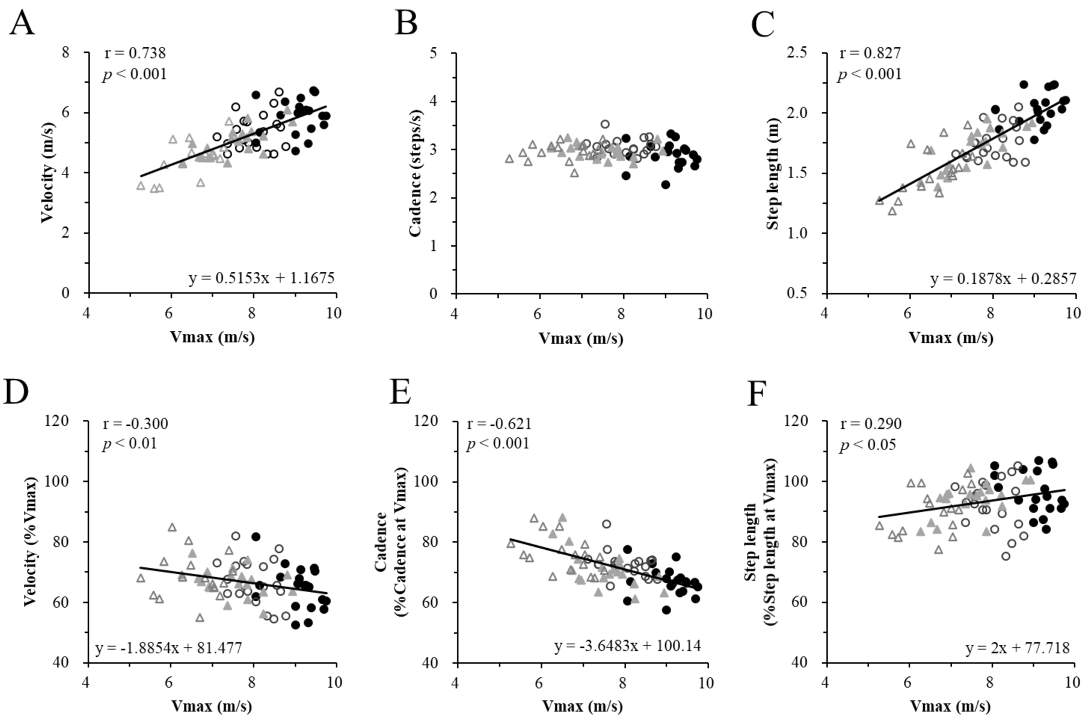

Figure 2-4. Correlation between maximal running velocity (Vmax) and: running velocity (A), cadence (B), and step length (C), as well as the same three parameters normalized to the Vmax (D-F) at the inflection point. Filled and open circles, and filled and open triangles represent the sprinters, distance runners, active athletes, and sedentary individuals, respectively. The correlations are all significant except for cadence (B).

Figure 2-4A-C depicts correlations between maximal running velocity and running velocity, cadence, and step length at the inflection point. There were significant positive correlations between Vmax and both velocity and step length at the inflection point (velocity: Fig. 2-4A, r = 0.738, $p < 0.001$; step length: Fig. 2-4C, r = 0.827, $p < 0.001$). Cadence at the inflection point had no correlation with Vmax, and was approximately constant at 3.0 ± 0.2 steps/s regardless of the subject group (Figure 2-4B). Figure 2-4D-F illustrates correlation for the same parameters shown in Figure 2-4A-C, but with values normalized to Vmax. Velocity and cadence show negative correlations (velocity: $r = -0.300$, $p < 0.01$; cadence: $r = -0.621$, $p < 0.001$), while step length has a positive correlation with Vmax ($r = 0.290$, $p < 0.05$).

2-4 Discussion

We investigated the relative contribution of cadence and step length changes as running velocity was modulated in four groups of subjects with different histories of engagement in running-specific training, utilizing the segmented regression method with two regression lines (Fig. 2-1). In spite of a large variation in maximal running velocity, the general characteristics of the V-C-S relationship were similar across the subject groups (Fig. 2-3) as well as across the data of individuals (Figs. 2-5, 2-6, 2-7, 2-8).

Basic characteristics of the V-C-S relationship

As expected, compared to the sprinters, maximal running velocities were progressively slower in the distance runners, active athletes and sedentary groups. There were significant differences between the sprinters and the other three groups, as well as between the distance runners and the sedentary individuals (Fig. 2-2A). Both cadence and step length at Vmax were well correlated with Vmax (Figs. 2-2B and C, respectively). Among the subject groups, the sprinters were the tallest and the sedentary group was the shortest. The strong correlation of step length with Vmax was well-preserved, however, even when step length was normalized to the subjects' heights (Fig. 2-2D). Thus, faster maximum running velocities were generally accomplished with both a higher cadence and longer steps. The minimum running velocity was common to all subject groups at 2.17 ± 0.45 m/s with a cadence of 2.62 ± 0.14 steps/s and a step length of 0.82 ± 0.17 m (Fig. 2-3A). It appears that a slower cadence would have required "hopping" rather than running, and for shorter step lengths it became similar to "jogging in place".

In all four subject groups, an abrupt change in the V-C-S relationship took place at the inflection point (Fig. 2-3, and Table 2-2). Velocity changes below the inflection point occurred mainly by modulating step length and velocity changes above the inflection point occurred mainly via cadence modulation. These characteristics were demonstrated in preceding studies conducted on sprinters and distance runners (Nummela et al., 2007; Weyand et al., 2000), and are particularly prominent in sprinters.

Running velocity at the inflection point has a significant positive correlation with Vmax (Fig. 2-4A). Thus, the faster the Vmax, the faster the velocity at the inflection point. A faster velocity at the inflection point is mainly attained by longer step length (Fig. 2-4C). However, this correlation was weak when it is normalized with the step length at the Vmax (Fig. 2-4F).

Overall, regardless of the training history, all groups had a similar relative step length quite close to the maximum step length (about 90%). Interestingly, the cadence at the inflection point has no correlation with Vmax and remained constant at about 3 steps/s (Figs. 2-4B). The history of the training influenced normalized cadence at the inflection point, that is, sprinters had a lower normalized cadence at the inflection point than the others, although in absolute terms cadence was the same. In the normalized plane (Fig. 2-3B) inflection points of the different groups are lined along the isovelocity curve of 65-70%. Scatter plots of all subjects of all the groups showed only a weak correlation between the Vmax and the velocity at the inflection point normalized with Vmax (Fig. 2-4D). In spite of the wide range of sports, and thus athletic modality of the subjects as well as their maximum running velocity, the inflection point appeared at a similar cadence (3.0 ± 0.2 steps/s) as well as at similar relative velocity (65-70%Vmax), across all groups. These results imply that the influence of running-specific training on cadence at the inflection point is minimal.

Functional meaning of the V-C-S relationship

Although the basic characteristics of the V-C-S relationship are common across different subject groups, the quantitative difference could be related to quality/quantity difference in running-specific training among groups.

In the present study, four groups of subjects, sprinters, distance runners, active athletes utilizing varying degrees of running but no running training, and sedentary individuals, were studied. Of course, the above order would also be expected for the maximal velocity from fastest to the slowest (Figure 2-2A). Sprinting and distance training involves running on a daily basis, and running (generally without specific running instruction) forms one aspect of training for many of the active athletes as well. It seems reasonable that some portion of the observed maximal velocities reflect differences in training.

Interestingly, step length at the inflection point also follows the same order as the maximal running velocity (Fig. 2-3A and Figs. 2-4C, F). In the velocity range below the inflection point, velocity change is mainly done with a change in step length; for energy-saving this is a more efficient strategy than is changing the cadence (Yanai & Hay, 2004). It would be beneficial for distance runners to run within this range as much as possible when their velocity is below the inflection point. Indeed, it was shown that at 4.4 m/s velocity, in the range below the inflection point, the step length was associated with better running economy in distance runners (Tartaruga et al., 2012). Therefore, we had hypothesized that the ability to run below the inflection point would be particularly developed in distance runners. However, sprinters and not distance runners increased velocity by elongating both absolute step length (Figure 2-4C) and relative step length (Figure 2-4F), all the way to the upper running velocity limit. Thus, our working hypothesis was rejected. Sprinters rarely train in the velocity range below the inflection point. Obviously, maximal velocity is crucial for sprinters. A faster velocity cannot be accomplished only with power, especially at the highest levels. Sprinters need to develop both power and economy to the upper limit, and inevitably and unintentionally develop mechanically efficient movements.

Chapter 2 Appendix

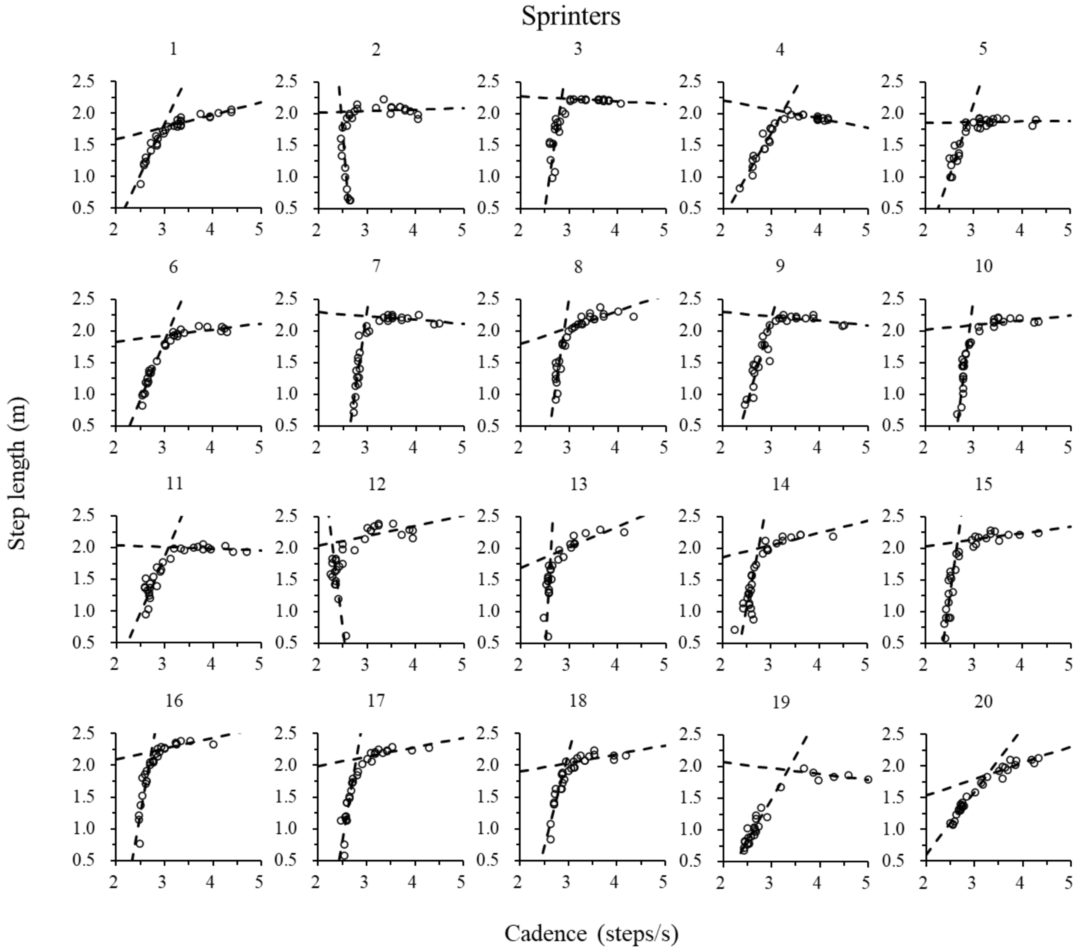

Figure 2-5. The relationship between cadence and step length for all the sprinters. The two dashed lines depict the regression lines computed from different data below and above the inflection point, respectively.

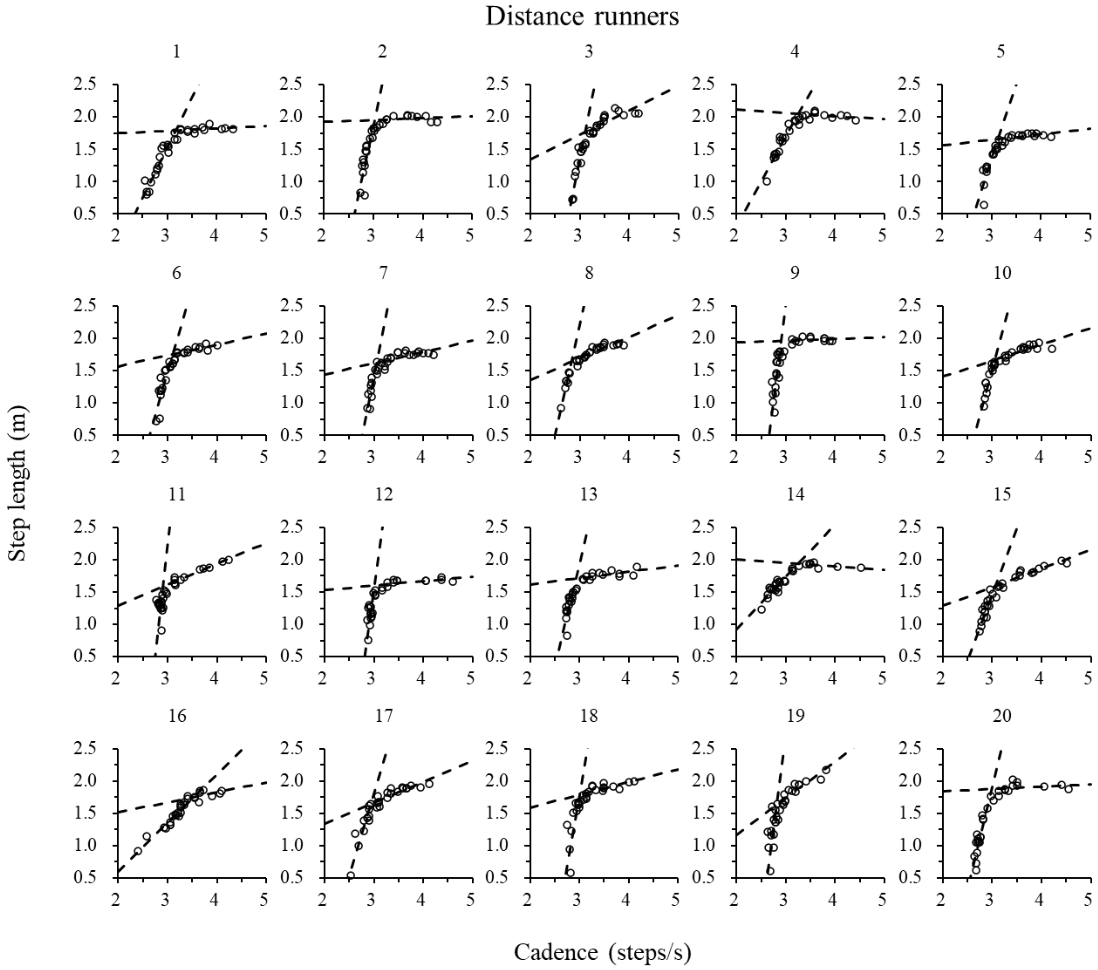

Figure 2-6. The relationship between cadence and step length for all the distance runners. The two dashed lines depict the regression lines computed from different data below and above the inflection point, respectively.

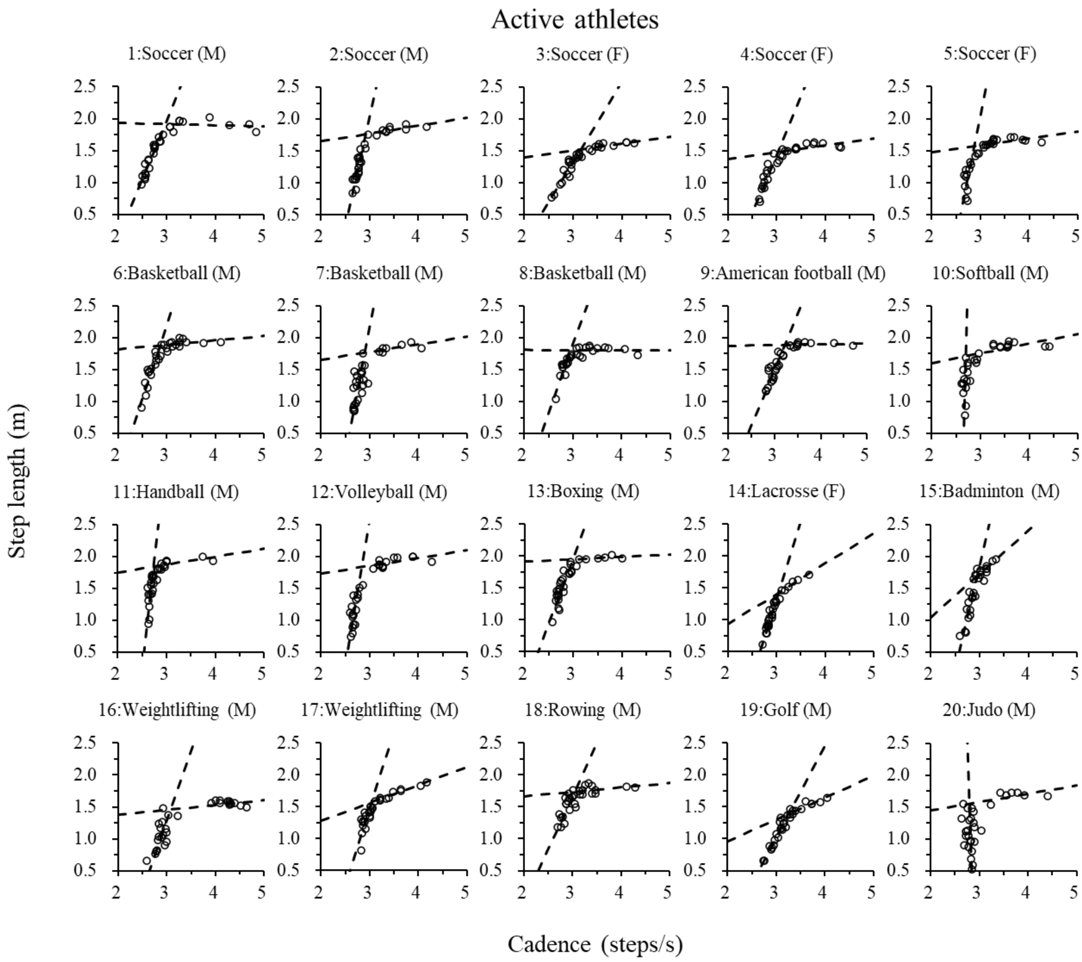

Figure 2-7. The relationship between cadence and step length for all the active athletes. The two dashed lines show the regression lines computed from different data below and above the inflection point, respectively. The title of each figure corresponds to each subject's sports experience. Characters in parentheses signify male or female subjects.

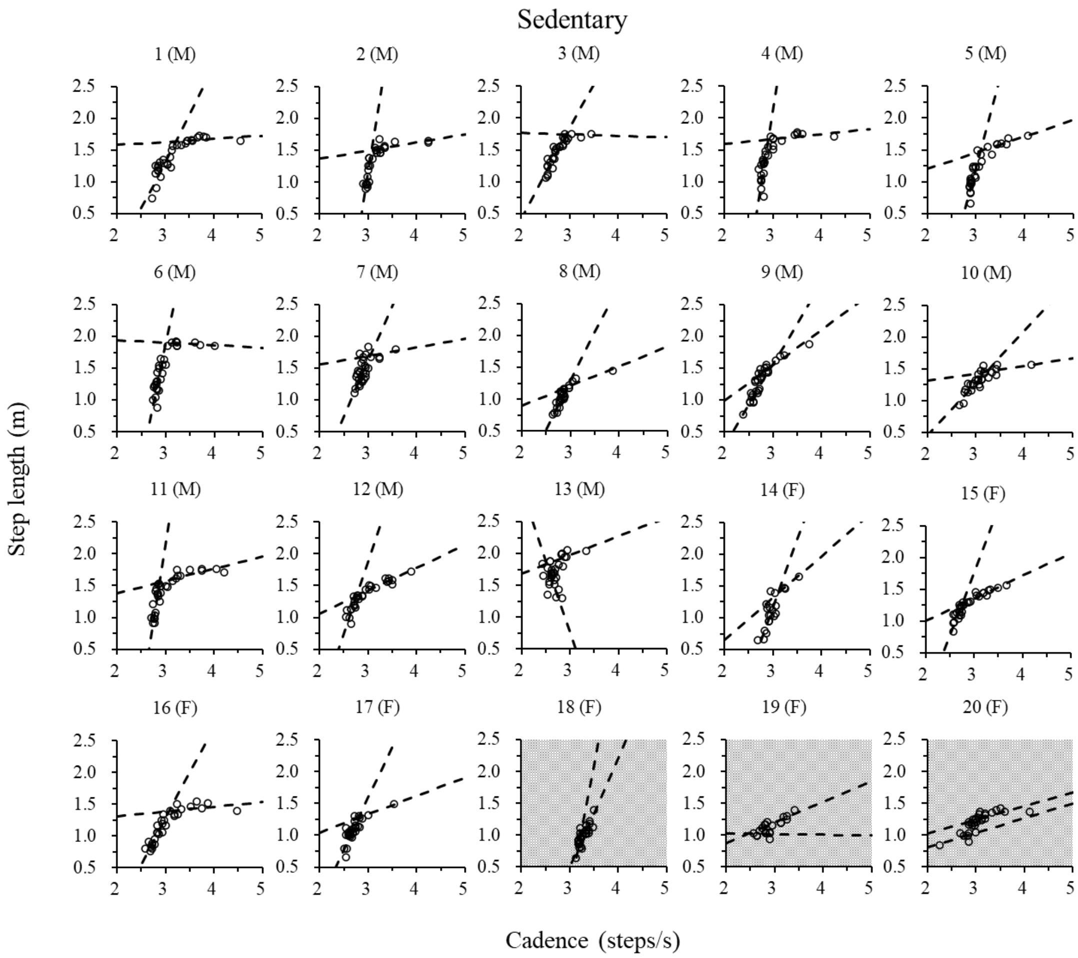

Figure 2-8. **The relationship between cadence and step length for all the sedentary.** The two dashed lines show the regression lines computed from different data below and above the inflection point, respectively. In the sedentary group, three subjects were excluded from data analysis: two subjects (No. 18 and No. 19) had estimated inflection point fell outside the range of the original data, and one subject (No. 20) showed two regression lines with almost the same slope giving the inflection point completely outside the range of measured data. Characters in parentheses signify male or female subjects.

Chapter 3

Spatiotemporal inflection points in human running: effects of growth and development.

3-1 Introduction

In Chapter 2, in spite of the wide range of athletic modalities of the subjects, and their maximum running velocity, the inflection point appeared at a similar cadence (3.0 ± 0.2 steps/s) and at similar a relative velocity (65-70%Vmax), across all groups. These results implied that the influence of running-specific training on the inflection point was minimal. If the effect of training does not affect the characteristics in the inflection point, the characteristics may reflect an innate function of humans, because humans naturally acquire individual running movement (宮丸, 2001).

There are many studies on the running ability at sprinting in childhood, but few studies have measured the effect of growth and development on basic running characteristics (V-C-S relationship) and growth and development (Schepens et al., 1998; Schepens et al., 2001). Schepens et al. reported that average cadence at running velocities below 11 km/h in children aged 2 to 12 years decreased from 4 to 2.5 steps/s due to the particular relationship (k/m) between stiffness (k) and body mass (m) of children. In addition, they reported that cadence at maximum running velocity remained constant (4 steps/s) regardless of age. Although there are reports on cadence at slower velocity range and maximum running velocity as described above, there have been no reports on inflection points in the V-C-S relationship. In Chapter 2, I showed that running characteristics in adults at wide running velocities is characterized by inflection points that the relative relationship between step length and cadence changes. The cadence at the inflection point converges to about 3.0 steps/s regardless of their different backgrounds in running training (Goto et al., 2021). It is still unclear, however, how and when in the growth and developmental stages this characteristic is established. Clarifying this issue may help improve running performance, including sprinting, in the young and children for proposing training methods as well as for promoting the normal development of running ability. Therefore, in this chapter 3, the changes in V-C-S characteristics with growth and development was examined in preschool children and children of 1-12 years of age.

3-2 Methods

Subjects

Forty-six children (1-12 years old) were recruited as participants in this study. The participants and parents of participants were informed of the purposes and procedures of the study by a verbal and written explanation. After that, they signed an informed consent form. This study was approved by the Human Research Ethics Committee in the Faculty of Sport Sciences, Waseda University. The experiments were conducted in accordance with the Declaration of Helsinki.

Experimental setup and tasks

Experiments were conducted on an all-weather straight track. Color marks were set on the line connecting the camera with the points of start and end in the center of the running path to confirm the runner's position on the image of the panning camera. A sagittal view of each participant was recorded by panning with a video camera (DMC-FZ300, Panasonic) placed approximately 10 m lateral to the center of the running path. An additional 1-10 meters were provided before and after the filming zone so that the subjects could accelerate and decelerate and thus maintain running velocity as constant as possible throughout the recording area. This acceleration distance differed in each trial and was selected by the subject. The video sampling frequency was 60 Hz.

Participants were asked to run along the path about 10-15 times at various velocities, which varied from slow to the fastest possible. The order of running with different velocities was randomized on a subject-by-subject basis. The subjects were directed to run at a particular running velocity. This instruction included requesting "run faster or slower than the previous trial". In addition, for young children, who did not understand the meaning of the instruction, measurements were taken by running multiple times towards their parents that stay at the endpoint of the running path or running with the parents. In particular, for toddlers aged 1 to 4 years, the fastest running velocity within multiple trials was used as the maximum running velocity during the sprint. The participants used their own shoes that they usually use.

Data analysis

Data analysis was performed by using playback software (QuickTime player, Apple Inc., USA). The running velocity, cadence, and step length were calculated on a trial-by-trial basis for each subject based on the video analysis. Mean running velocity (m/sec) was calculated by dividing the length of the path (m) by the time taken (sec) to run over the path. The instant at which the subject passed the start and the endpoint was identified from the position of the chest relative to the color markers. Mean cadence (steps/sec) was calculated by dividing the number of steps by the time taken to cover that distance. The number of steps was counted from the first ground contact with the path to the last ground contact before passing the end point. The duration utilized was defined as the time between the instant of first foot-contact after the start position and that of the last foot-contact before the end. Mean step length (m) was calculated by dividing the mean running velocity (m/sec) by the mean cadence (steps/sec). Step length was also expressed as the ratio of the step length (m) to the height (m) of each subject in order to examine the influence of the physical characteristics of the subjects. The fastest among all trials by each subject was designated as their maximal running velocity.

The principal analyses for the spatiotemporal running characteristics of each subject were performed with MATLAB version R2020a (The MathWorks, Inc., USA). To quantitatively analyze the critical point at which the relative contribution of spatiotemporal adjustment changed (cadence vs. step length), we utilized the segmented regression method (Goto et al., 2021).

Statistical analysis

Statistical analysis was performed using SPSS Statics 27 software (IBM, USA). Running velocity, cadence, and step length at the maximal running velocity were tested for a normal distribution using the Shapiro-Wilk test. Maximum running velocity and step length at maximal running velocity exhibited normal distributions. Pearson's and Spearman's correlations were performed to analyze the relationship between subject age and all parameters at maximal running velocity, and significance was accepted at $p < 0.05$. The data are presented as mean and standard deviation (mean ± SD).

3-3 Results

Figure 3-1A-C depicts correlations between age of subject and running velocity, cadence, and step length at the maximal running velocity. There were significant positive correlations between age of subject and running velocity and step length at the maximal running velocity (velocity: Fig. 3-1A, $r = 0.920$, $p < 0.001$; step length: Fig. 3-1C, $r = 0.903$, $p < 0.001$). There were no significant correlations between age of subject and cadence at the maximal running velocity (Figure 3-1B).

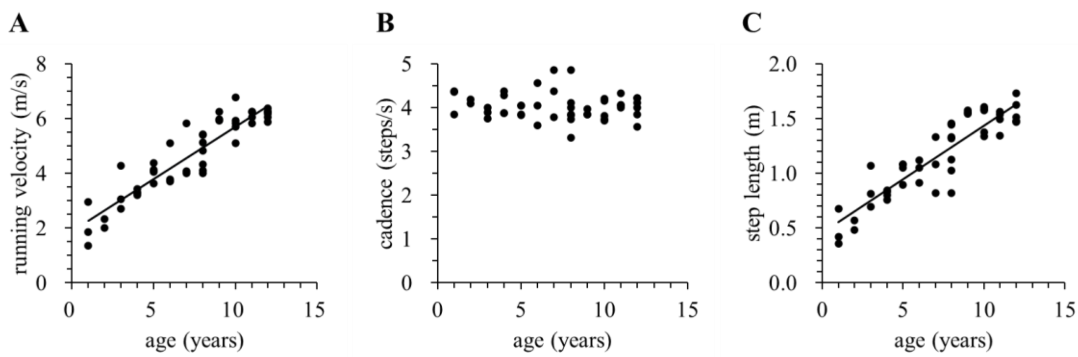

Figure 3-1. Correlation between age of subjects and: running velocity (A), cadence (B), and step length (C) at the maximal running velocity.

Figure 3-2A - C depicts correlations between age of subject and running velocity, cadence, and step length at the minimal running velocity. There were significant correlations between age of subject and cadence and step length at the minimal running velocity (cadence: Fig. 3-2B, $r = -0.802$, $p < 0.001$; step length: Fig. 3-2C, $r = 0.537$, $p <$

0.001). There were no significant correlations between age of subject and minimal running velocity (Figure 3-2A).

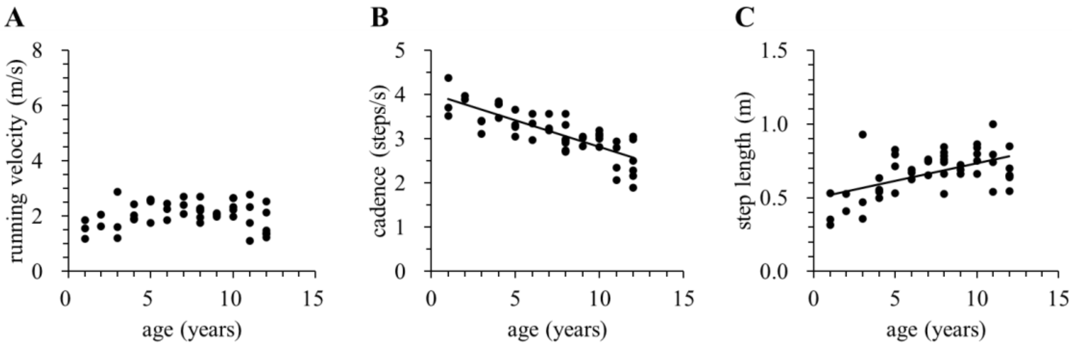

Figure 3-2. Correlation between age of subjects and: running velocity (A), cadence (B), and step length (C) at the minimal running velocity.

Table 3-1 shows the number of subjects of each age and the number and percentage of subjects who showed inflection points. The percentage of inflection points was highest for 11 to 12 years old and lowest for 1 to 2 years old. The inflection point could theoretically be calculated in any group of data. However, as in Chapter 2, the subjects whose inflection points did not fall in the velocity range of measured data points were excluded here from the judgment as having an inflection point.

Table 3-1. The number of the subject of each age and the subject who had inflection point

age (years)	the number of subjects	the number of subjects who acquired inflection point	
1	3	0	0%
2	2	0	0%
3	3	0	0%
4	4	1	25%
5	4	1	25%
6	3	0	0%
7	3	2	67%
8	6	3	50%
9	3	3	100%
10	5	3	60%
11	4	3	75%
12	6	6	100%

Figure 3-3 shows typical examples of the relationship between cadence and step length for 10-12 years old children.

Figure 3-3 shows typical examples of the relationship between cadence and step length for children 1-12 years old. Inflection points began to appear around 7, and similar V-C-S relationships were observed in children aged 10 to12 years (upper part of the figure). For children aged 10 to12 years, the parameters at the inflection point were running velocity; 4.75 ± 0.93 m/s, cadence; 3.35 ± 0.33 m/s, and step length; 1.40 ± 0.17 m, respectively. On the other hand, children aged 1 to 6 could hardly observe clear inflection points (lower part of the figure). The children of this age group are characterized with that changes in running velocity changes appear to depend mainly on cadence change than step length change.

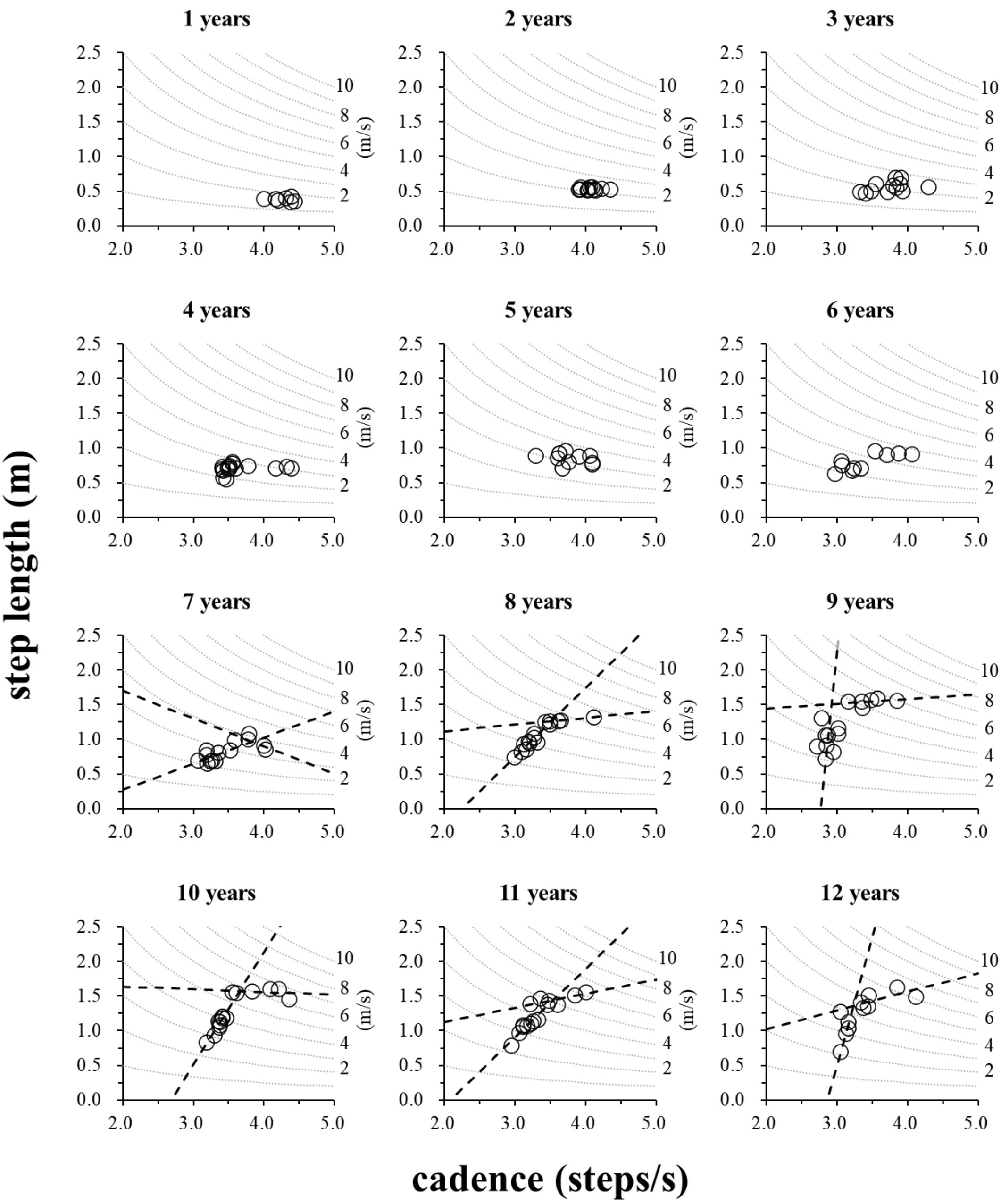

Figure 3-3. The relationship between cadence (steps/s, horizontal) and step length (m, vertical) relative to running velocity (m/s) in each representative example of each age (1 to 12 years old). The subjects whose inflection points were calculated are depicted by two regression lines (dashed lines).

3-4 Discussion

The purpose of this Chapter is to clarify the relative contribution of cadence and step length changes to running velocity (V-C-S relationship) with growth and development, utilizing the segmented regression method with two regression lines. In this study, different V-C-S relationship changes were obtained depending on the stage of growth and development (Figures 3-3). The clear inflection points as seen in Chapter 2 for adults were especially observed in children over 10 -12 years (Figure 3-3).

The characteristics of the V-C-S relationship in children

V-C-S relationships in 46 children in the range of 1-12 years old showed different characteristics depending on ages. First, the increase in maximum running velocity between the ages of 1-12 was due to increased step length (Figs. 3-1A, C). This result is consistent with previous studies of children's sprint ability; that is, the increase in maximum running velocity in childhood is due to the increase in step length which might be accomplished with the increase in their height (Schepens et al., 1998; 宮丸, 1975; 斉藤, 1981; 辻野 & 後藤, 1976). On the other hand, it has been reported that cadence at the maximal running velocity hardly changes with growth and development (宮丸, 1975; 斉藤 & 伊藤, 1995; 辻野 & 後藤, 1976). The value has been reported to be about 4.0 steps/s in the previous study, and cadence in this study showed a similar value (4.02 ± 0.24 steps/s) (Figure 3-1B). This fact strongly suggested that the maximum cadence is congenitally determined. Furthermore, 4.0 steps/s is about the same as the cadence of the sedentary adults studied in the Chapter 1 (Figs. 2-2B and 2-3A), and all the other three groups (sprinters, distance runners, and active athlete) had greater cadence than 4.0 steps/s. This might mean that the main goal of athletic training is to increase cadence, or that athletes including runners congenitally have greater cadence than non-athletes. This is a very interesting topic for future studies.

The minimum running velocity was similar for all subjects (1.74 ± 0.54 m/s). However, unlike the maximum running velocity parameters, there was a negative correlation between age and cadence at minimum running velocity (Figure 3-2B). It has been reported that preschool children aged 1 to 2 years who started running movement have shorter flight times and shorter step lengths (宮丸, 2001). The V-C-S relationship of 1-2 years old children in Figure 3-3 shows that they adjust their running velocity within a very narrow range compared to older children (e.g., Figs. 3-3). In particular, for preschool children, velocity change was caused mainly by cadence changes. While the cadence at maximal running velocity does not change, the cadence at minimal running velocity decreases with growth and development. This seems to be due to the increase in stiffness and body mass with development up to the age of 12, as reported by Schepens et al. (1998). In addition, this decrease in cadence also is considered due to the increase in their unsupported period (flight time). This increase may have been caused by increased muscle strength or stiffness, which is sufficient to support the body's center of gravity. This result seems to be confirmed because the step length at the minimal running velocity showed a weak positive correlation (Fig. 3-2C). It is possible that the older children understood the instruction and tried to run at a lower running velocity, resulting in an unintentional hopping jump.

The inflection point of the V-C-S relationship in children

In the children's V-C-S relationships, characteristics similar to those obtained in Chapter 2 were especially observed in children over 9 years old (Table 3-1, Figure 3-7). For children in this age group, inflection points could be clearly obtained with the segmented regression method, while in the younger age group the inflection point was not clearly obtained. Although this is just a qualitative result from observation, it suggests that the age around 9 would be the point at which the relative contribution of cadence and step length change for running velocity approached to that observed in adults. This age corresponds well to that of secondary sexual characteristics. In other words, the transition to the adult pattern of V-C-S characteristics might be caused secondarily to the particular changes in the physical characteristics (increase in height and weight). This is also an issue of future studies.

For children under the age of 9 in this study, the change in running velocity was produced mainly with the change in cadence (Figs. 3-3). For the calculation of inflection points by the segmented regression method, it is hypothesized that a inflection point exists where there is a change in the relative contribution between step length and cadence with the change in running velocity. For this reason, the inflection point may not be calculated correctly for subjects who show a change in running velocity due to one or the other spatiotemporal parameter. This was also the case in three sedentary subjects in Chapter 2. As a characteristic of the V-C-S relationship in Chapter 2 adults, in spite of the wide range of athletic modalities of the subjects, and their maximum running velocity, the inflection point appeared at a similar cadence (3.0 ± 0.2 steps/s). However, the cadence was higher than 3.0 steps/s even at the minimum running velocity for the children younger than 10 years old, especially for preschool children. One of the reasons for the inflection point may be that the cadence at the lowest running velocity needs to be at least 3.0 steps/s lower. In order to lower the cadence, you need to increase the time for one step. This should be accomplished by increasing the flight time in most subjects. This leads to the acquisition of longer stride length to the propulsion direction or higher jump to the vertical direction. In younger children, the lack of sufficient lower extremity muscle strength and stiffness to lift the body's center of gravity would inevitably result in a higher cadence. This suggests that an increase in flight time may be necessary as one of the factors that induces explicit inflection points along the course of growth and development.

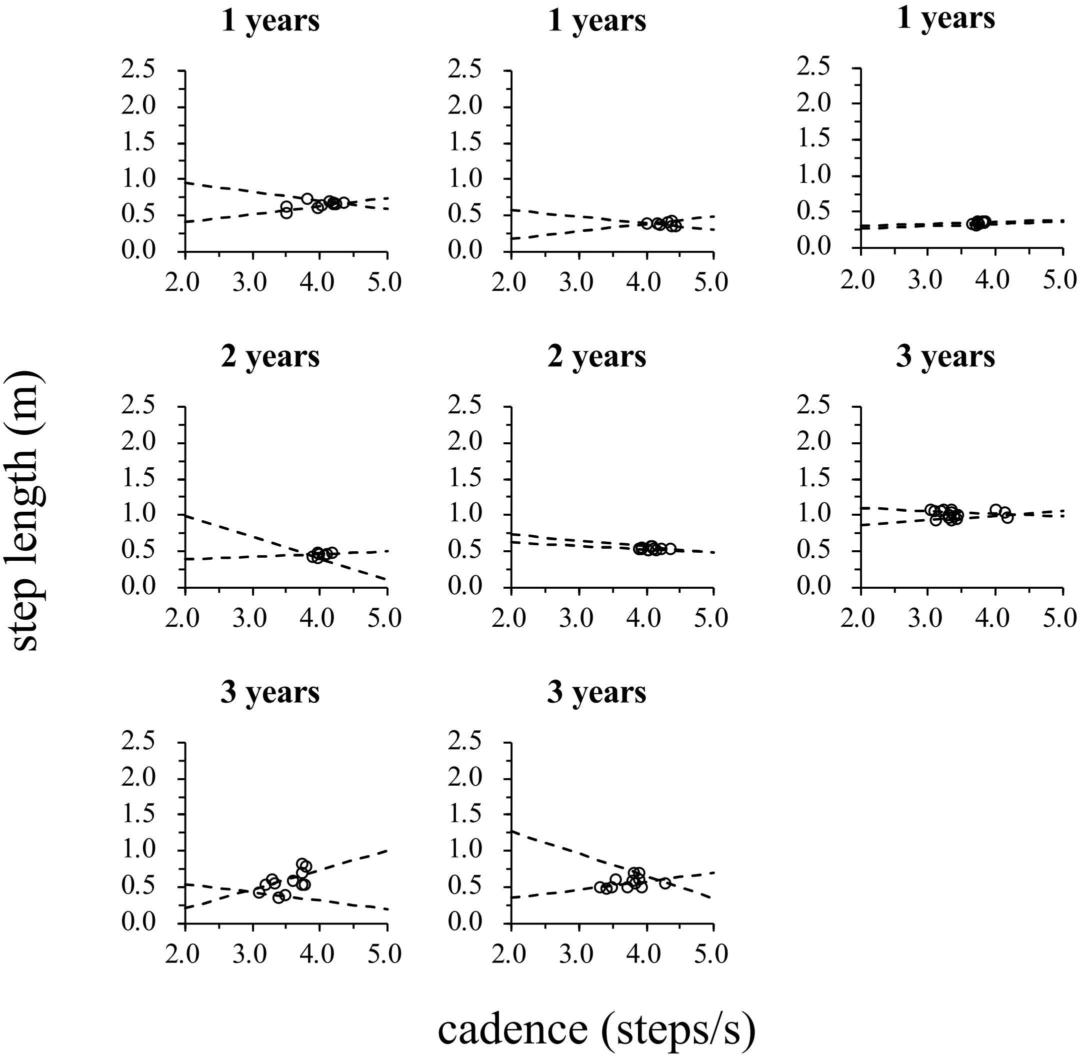

Figure 2-4. The relationship between cadence and step length for children from 1 to 3 years old.

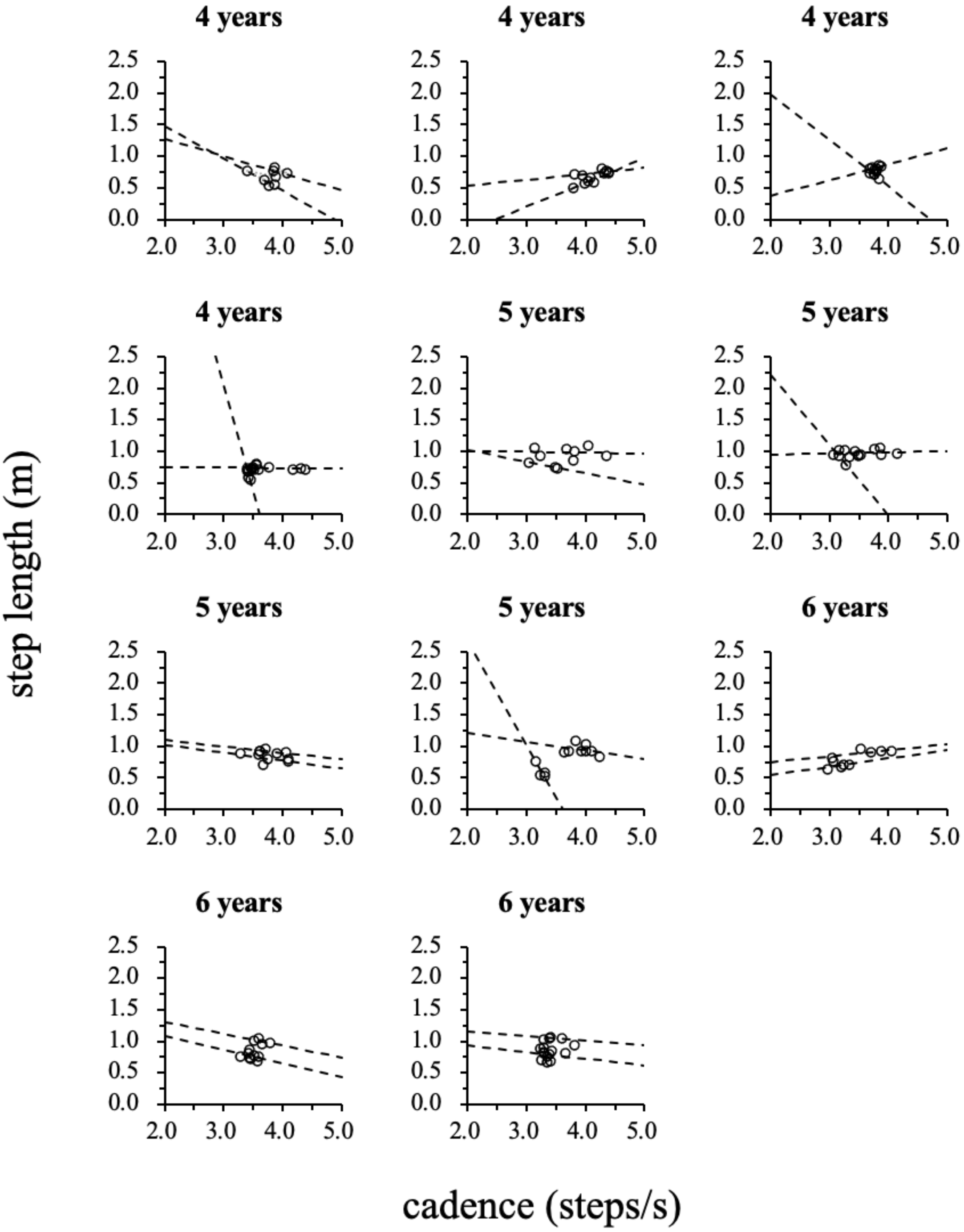

Figure 3-5. The relationship between cadence and step length for children from 4 to 6 years old.

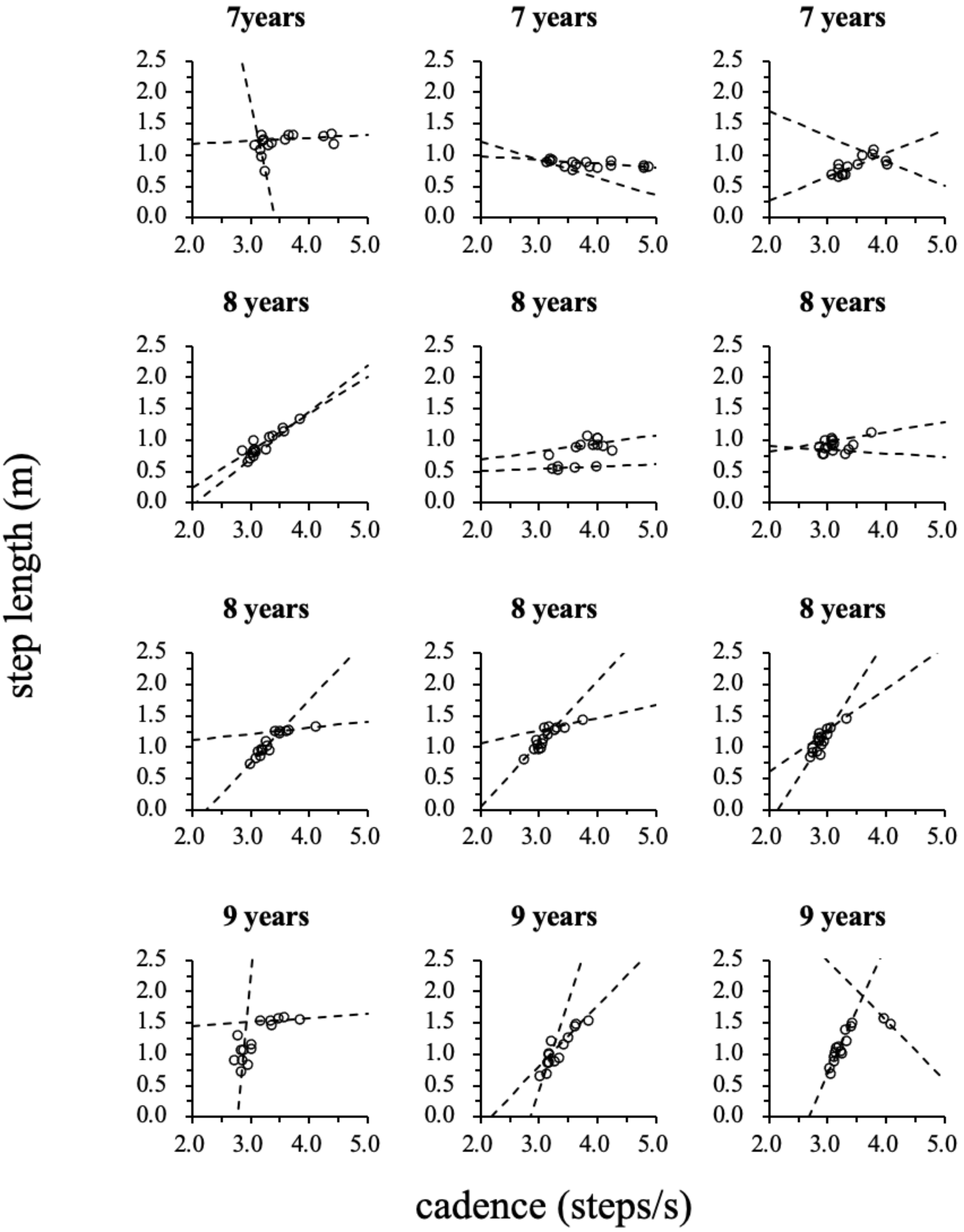

Figure 3-6. The relationship between cadence and step length for children from 7 to 9 years old.

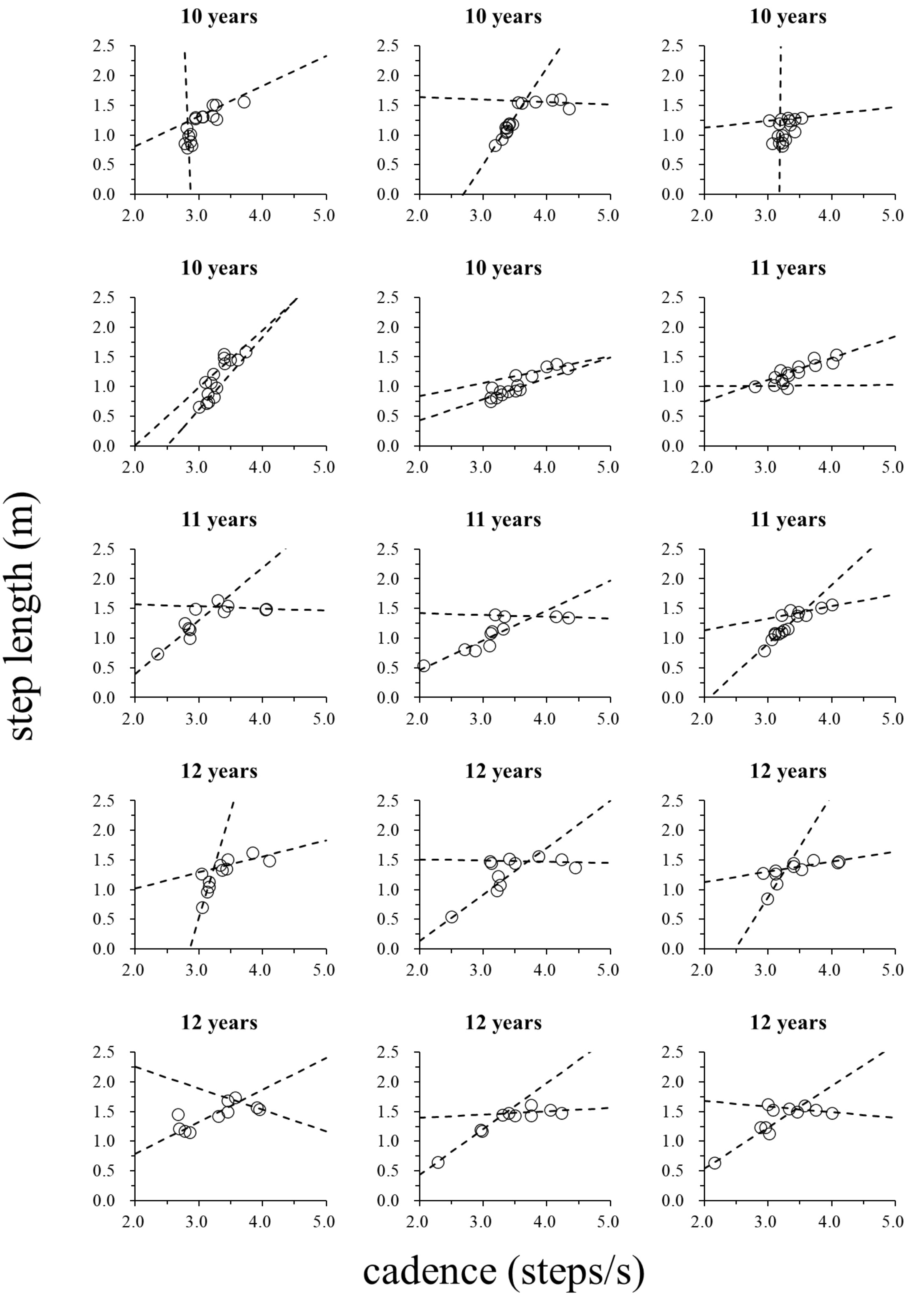

Figure 3-7. The relationship between cadence and step length for children from 10 to 12 years old.

Chapter 4

Foot strike pattern and sprint performance in preschool children

4-1 Introduction

The foot strike pattern is one of the indices to evaluate the running movement of individuals. The foot strike pattern can be classified into three types: a rearfoot strike pattern (RF), in which the heel first touches the ground; a midfoot strike pattern (MF), in which the heel and the metatarsal head touch the ground simultaneously; and a forefoot strike pattern (FF), in which the metatarsal head or the ball of the thumb first touches the ground before the heel strikes down (Altman & Davis, 2012; Forrester & Townend, 2015; Lieberman et al., 2010).

信岡 et al. (2020) clarified the actual state of foot strike patterns in children of 6 – 12 years of age, and the relationship between foot strike pattern and sprinting performance. The proportions of children with midfoot and forefoot strike pattern are lower than those in adults, suggesting that the foot strike pattern is influenced by factors such as physical development and the ground strike motion of the swing leg. However, it is unclear whether these factors can also be applied to younger preschool children.

Therefore, the purpose of this study was to clarify the actual foot strike pattern of preschool children (3 to 6 years), and its relationship with the indices related to sprint performance, such as maximum running velocity, step frequency, and step length.

4-2 Methods

Participants

The participants were 282 children (135 boys and 147 girls) ranging from 3 to 6 years old (body height, 1.08 ± 0.07 m; body mass, 17.6 ± 2.8 kg). This study was approved by the Human Research Ethics Committee in the Faculty of Sport Sciences, Waseda University. The experiments were conducted in accordance with the Declaration of Helsinki.

Experimental setup and tasks

The experiment was performed with a 25m sprint test conducted with two subjects in individual lanes side by side. To prevent the subjects from intentionally slowing down just before the goal, a kindergarten staff member stood 5 m beyond the actual goal point as in 有川 et al. (2004), and instructed the children to run at maximal effort until the 30 m point. Two digital video cameras (JVC GC-PX1, frame rate: 300 frames/s) were set up on both sides of the running path at the 11-m point, and fixed photography was performed using a tripod. To capture the running motion from start to goal, two digital video cameras (JVC GC-PX1, frame rate: 60 frames/s) were set up on each side of the 12.5m points of the running track, and panning recording was performed using a tripod. Panning photography was conducted using a tripod. A cone-shaped marker was placed on the line connecting the camera and the point every 5 m in the center of each running path to confirm the runner's position on the panning camera image.

The average running velocity of each 5-meter section from the 5-meter point to the 25-meter point, the maximum running velocity in the entire section, and the cadence and step length in the section where the maximal running velocity was recorded were calculated based on the video images from the camera that took panning record. The ground contact time and flight time were calculated based on the static camera images of the running movement from 9m to 11m. The ground contact and toe off were determined as follows: (1) the ground contact started when it was confirmed that the subject's foot or a part of it was stationary, and (2) the ground contact ended when it was confirmed that the toe of the grounded foot moved.

In order to remove the influence of the preschool children's height and to examine the functional running ability, the indexes for cadence and step length were calculated using Alexander and Goldspink (1977) formula, which removes the physical influence of lower limb length, as

$$\text{cadence index} = \text{cadence} \cdot (\text{lower limb length} \cdot g^{-1})^{1/2}$$

$$\text{step length index} = \text{step length} \cdot \text{lower limb length}^{-1},$$

where g is the gravitational acceleration.

The lower limb length is the product of each age's average lower limb length ratio in 首都大学東京 (2007) and the measured height of the subject. In addition, since it is important to shorten the ground contact time and increase the flight time (increase the step length) during sprinting, the ratio of ground contact time (CT) to flight time (FT) was calculated as the related index.

Statistical analysis

IBM SPSS Statistics 27 was used as the statistical analysis software. A first-order approximation equation representing the relationship between the child's age and the maximum velocity was obtained, and the residuals from the maximum velocity estimated from the child's age were calculated. The mean and standard deviation of the residuals of the maximum velocity, cadence index, step length index, ground contact time, and flight time for each foot strike pattern and gender were calculated. For comparison of each measurement item among foot strike patterns, one-way analysis of variance was used when normality was observed in all three groups (rearfoot, midfoot, and forefoot strike pattern) by the Shapiro-Wilk test, and multiple comparisons by the Tukey-HSD method were conducted for items with significant F values. All significance levels were set at less than 5%.

4-3 Results

Table 4-1 shows the percentage of the foot strike pattern for each gender. The proportion of rearfoot strike patterns was the largest for both sexes, and the proportion of midfoot and forefoot strike patterns decreased in that order. At five years of age, the proportion of midfoot strike patterns increased in both genders.

Table 4-1. Foot strike pattern of subjects (%)

		all	3 years	4 years	5 years
RF	boys	80.0	87.2	88.4	65.1
	girls	74.6	78.0	90.9	55.6
MF	boys	13.6	10.3	4.7	25.6
	girls	19.2	14.6	6.8	35.6
FF	boys	6.4	2.6	7.0	9.3
	girls	6.2	7.3	2.3	8.9

Rearfoot strike pattern (RF) , Midfoot strike pattern (MF) , Forefoot strike pattern (FF)

The relationship between the age in months and the maximal running velocity of the subjects (boys: y = 0.023x + 3.010, r = 0.71, $p < 0.001$, girls: y = 0.021x + 3.117, r = 0.73, $p < 0.001$) is shown in Figure 4-1. The residuals of the maximal velocity, cadence index, and step length index for boys and girls are shown in Figure 4-2, respectively. The one-way analysis of variance showed a main effect for cadence index for boys ($F_{(2, 127)}$ = 1.385, $p < 0.01$; The results of the Tukey-HSD test showed that the cadence index (mean ± SD) were significantly higher in the midfoot (1.04 ± 0.07) and the forefoot (1.06 ± 0.07) than in the rearfoot (0.98 ± 0.08). On the other hand, no statistically significant difference was observed in the step length index.

The ground contact time, flight time, and contact flight ratio for boys and girls are shown in Figure 4-3. The one-way analysis of variance showed a main effect in the ground contact time for boys and girls and the ratio of contact time to flight time for girls (ground contact time for boys: $F_{(2, 127)}$ = 10.974, $p < 0.001$; ground contact time for girls: $F_{(2, 127)}$ = 10.974, $p < 0.001$; ratio of ground contact time to flight time for girls: $F_{(2, 127)}$ = 7.277, $p < 0.01$). The Tukey-HSD test showed that the ground contact times of boys and girls were higher in the midfoot strike pattern (boys: 0.14 ± 0.01 s, girls: 0.15 ± 0.01 s) and in the forefoot strike pattern (boys: 0.14 ± 0.01 s, girls: 0.14 ± 0.01 s) than in the rearfoot strike pattern (boys: 0.16 ± 0.01 s, girls: 0.16 ± 0.01 s). There was no significant difference in the flight time between boys and girls. The Tukey-HSD test showed that the ratio of ground contact time to flight time for girls was higher in the midfoot strike pattern (0.57 ± 0.14 s) and the forefoot strike pattern (0.61 ± 0.09 s) than in the rearfoot strike pattern (0.48 ± 0.13 s).

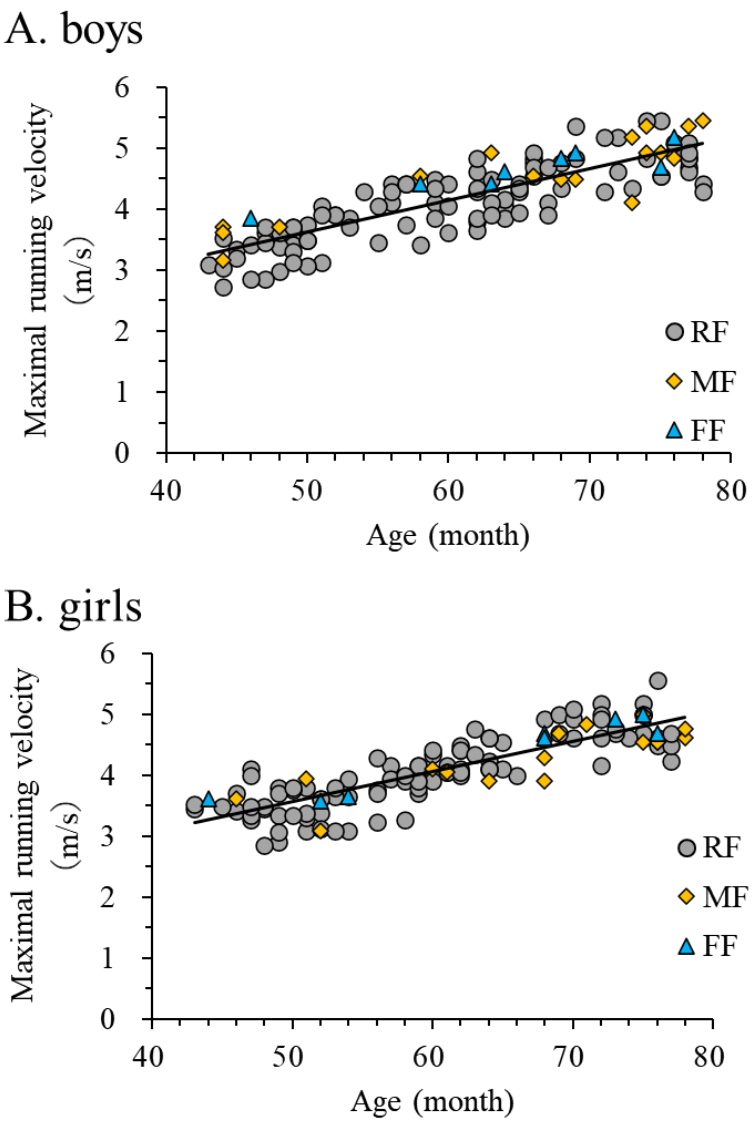

Figure 4-1. Relationship between the age in months and the maximum velocity in boys (A) and girls (B). Rearfoot strike pattern (RF) , Midfoot strike pattern (MF) , Forefoot strike pattern (FF)

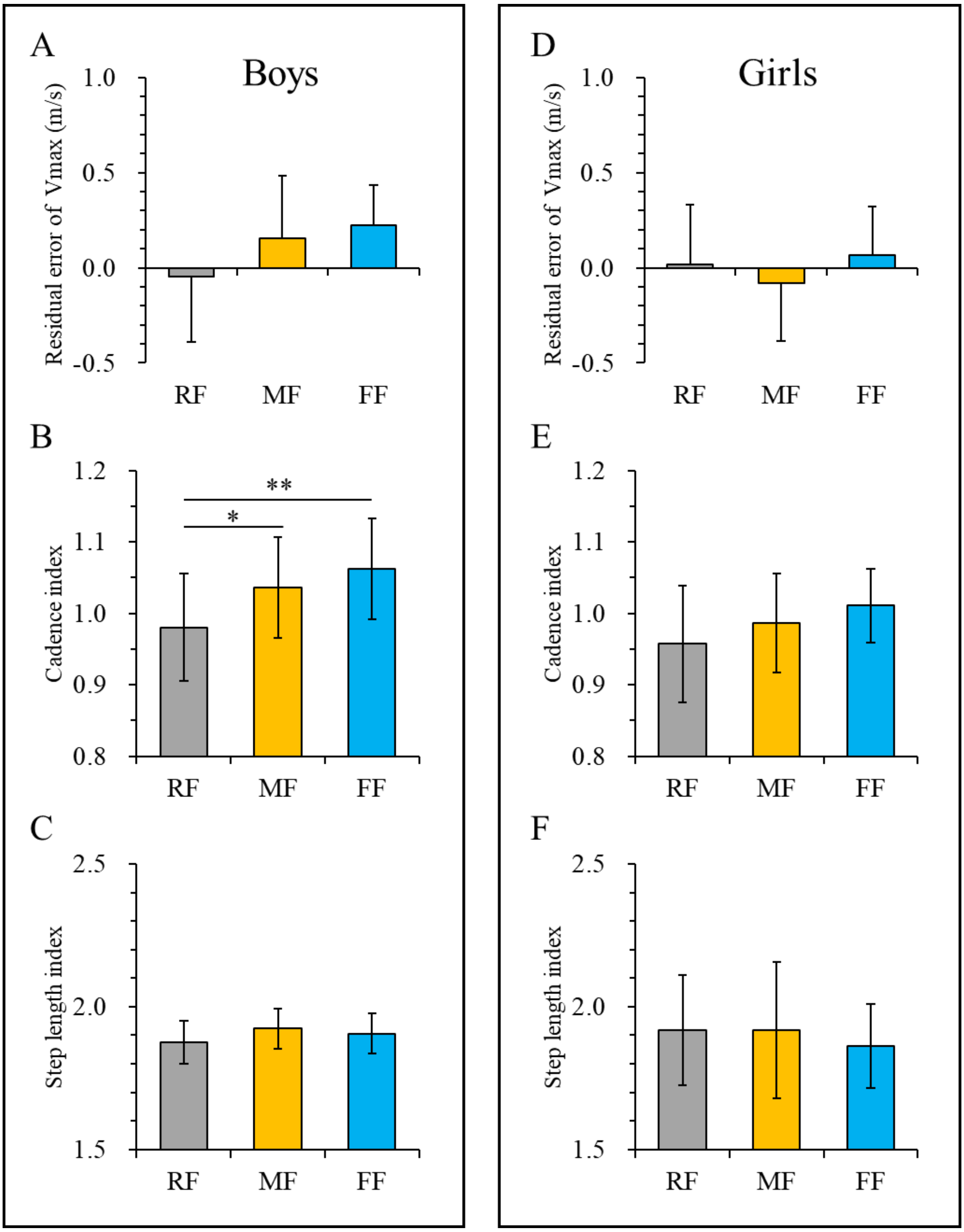

Figure 4-2. Comparison of residuals of maximum velocity, cadence index, and step length index for each foot strike pattern (rearfoot strike pattern (RF) ， midfoot strike pattern (MF) ， forefoot strike pattern (FF)) for boys (A, B, C) and girls (D, E, F) *; p < 0.05, **; p < 0.01

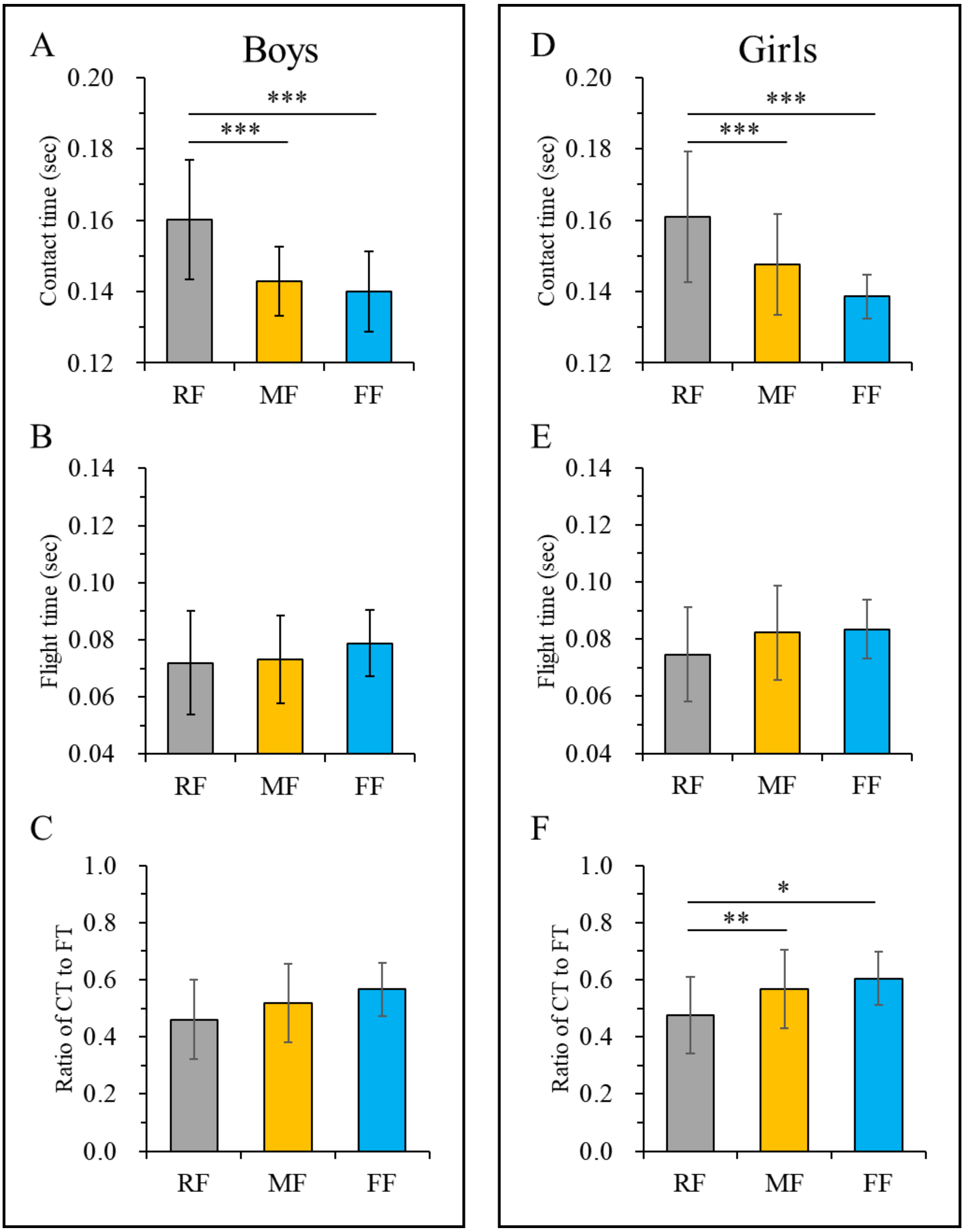

Figure 4-3. Comparison of residuals of contact time, flight time, and ratio of contact time (CT) to flight time (FT) for each foot strike pattern (rearfoot strike pattern (RF) , midfoot strike pattern (MF), forefoot strike pattern (FF)) for boys (A, B, C) and girls (D, E, F) *; $p < 0.05$, **; $p < 0.01$, ***; $p < 0.001$

4-4 Discussion

The purpose of this chapter was to clarify the actual foot strike pattern of young children and the differences in the indices (maximum running velocity, cadence index, step length index, ground contact time, and flight time) related to maximum running velocity and sprint performance according to the foot strike pattern. In the following, the characteristics of foot strike patterns and sprinting performance are discussed. Then, the relationship between the differences in foot strike patterns and the maximum running velocity is discussed.

4-4-1 Percentage of foot strike patterns in preschool children

Forefoot and midfoot striking patterns are considered desirable in instructional manuals for sprinting (Bosch & Klomp, 2005). In a previous study (信岡 et al., 2015) that investigated the relationship between foot strike pattern and sprinting performance in elementary school children using the same method as the present study, the residual difference between the maximum running velocity estimated from the age of the elementary school children and the measured maximum running velocity was negative for boys and girls with a rearfoot strike pattern and positive for boys and girls with a midfoot strike pattern and a forefoot strike pattern. In a previous study, the residual difference between the maximum running velocity and the measured maximum running velocity was negative value for boys and girls with the rearfoot strike pattern and positive value for boys and girls with the midfoot and forefoot strike patterns (信岡 et al., 2020). A similar trend was obtained in the present study, but no significant difference was found.

The most common foot strike pattern among the analyzed preschool children was the rearfoot strike pattern in both sexes. Studies with adults have reported that under conditions of high running velocity, half of the subjects run in a rear foot strike pattern, while the other half transition to midfoot or forefoot (Breine et al., 2014; Keller et al., 1996). The percentage of foot strike patterns in toddlers in the present study was similar to the percentage reported by 信岡 et al. (2020) for elementary school children (Figure 4-4). These suggest that the percentage of foot strike patterns may not change with growth and development in preschool children. In an adult study, it was reported that the forefoot strike pattern resulted in a greater force exerted by the triceps surae during the ground contact phase (Perl et al., 2012). In preschool children, muscle strength is undeveloped, so the effect of muscle strength is considered to be less than in adults or children after the secondary sexual characteristics. However, since it is difficult for them to run fast while grounding and supporting their body with their forefoot, they may be running with a rearfoot strike pattern as in previous studies.

4-4-2. **Relationship between foot strike pattern and ground contact time and flight time**

Ground contact time and flight time are related to step frequency and step length, which are determinants of running velocity (Figures 1 and 2). Studies in adults have shown that ground contact time is negatively correlated with maximal running velocity (Weyand et al., 2000; 信岡 et al., 2015) reported that ground contact time was negatively correlated with maximum running velocity and cadence index. Flight time was positively correlated with step length index during sprinting in children (信岡 et al., 2015). In the present study, the ground contact time of the midfoot and forefoot strike patterns was shorter than that of the rearfoot strike pattern in boys and girls (Figure 4-3A, D). However, unlike the previous studies (信岡 et al., 2020), there was no statistically significant difference in flight time. The ratio of CT to FF, which is the value obtained by dividing the flight time by the ground contact time, was larger for girls in the following order: rearfoot strike pattern, midfoot strike pattern, and forefoot strike pattern (Figure 4-3E). For boys, the cadence index was higher for the midfoot and forefoot strike patterns with shorter ground contact time than for the rearfoot striking pattern. However, it was not statistically significant for girls. However, this trend is similar to that reported by 信岡 et al. (2015) and suggests that differences in ground contact type affect ground contact time and cadence index.

As a characteristic of the running motion of children with a high cadence index, it has been reported that the thigh part of the rear swing leg is positioned more forward at the time of ground contact. The lower leg part of the supporting leg is tilted more forward in the sprinting motion (末松 et al., 2008). In other words, in the stagnation period just before ground contact, the characteristic of "scissors" both legs (i.e., the angle between the left and right thighs in the sagittal plane becomes smaller) and ground contact while swinging the leg on the side of ground contact backward may be responsible for the short ground contact time and high running velocity (阿江, 2001; 信岡 et al., 2015). On the other hand, there were no statistically significant differences in flight time or step length index among the groups of different foot strike patterns. It is important to increase the flight distance (step length) to increase running velocity. However, it is more difficult for underdeveloped preschool children to lift their own body's center of gravity into the air compared to adults and adolescents. This may be due to the fact that muscle strength and muscle-tendon stiffness are not sufficiently developed to increase step length.

This study examined the foot strike patterns in preschool children sprinting using a video camera-based video analysis technique. In running instruction textbook, ground contact with the forefoot, such as the toes or ball of the big toe, is desirable (Anderson, 2019; Bosch & Klomp, 2005), and many adults and excellent track and field athletes have been reported to the ground with the forefoot (Breine et al., 2014; Keller et al., 1996).

However, in this study, it was found that approximately more than 70% of the preschool children had a rearfoot strike pattern. The foot strike pattern is influenced by the strength of the impact on the foot at ground contact (E. A. Nigg, 1997), muscle strength to support the body (Perl et al., 2012), and leg movement (Hasegawa et al., 2007; Williams et al., 1987). Previous studies suggested that the approach to improve the sprinting ability of elementary school children is the need to achieve sprinting in the forefoot and midfoot strike patterns as the children's physical development improve their ability to exert force and improve their leg movements.

Further investigation and validation of methods to improve the grounding motion are needed. It will be necessary to investigate the effects of training interventions and their relationship with growth and development longitudinally over a more extended period of time.

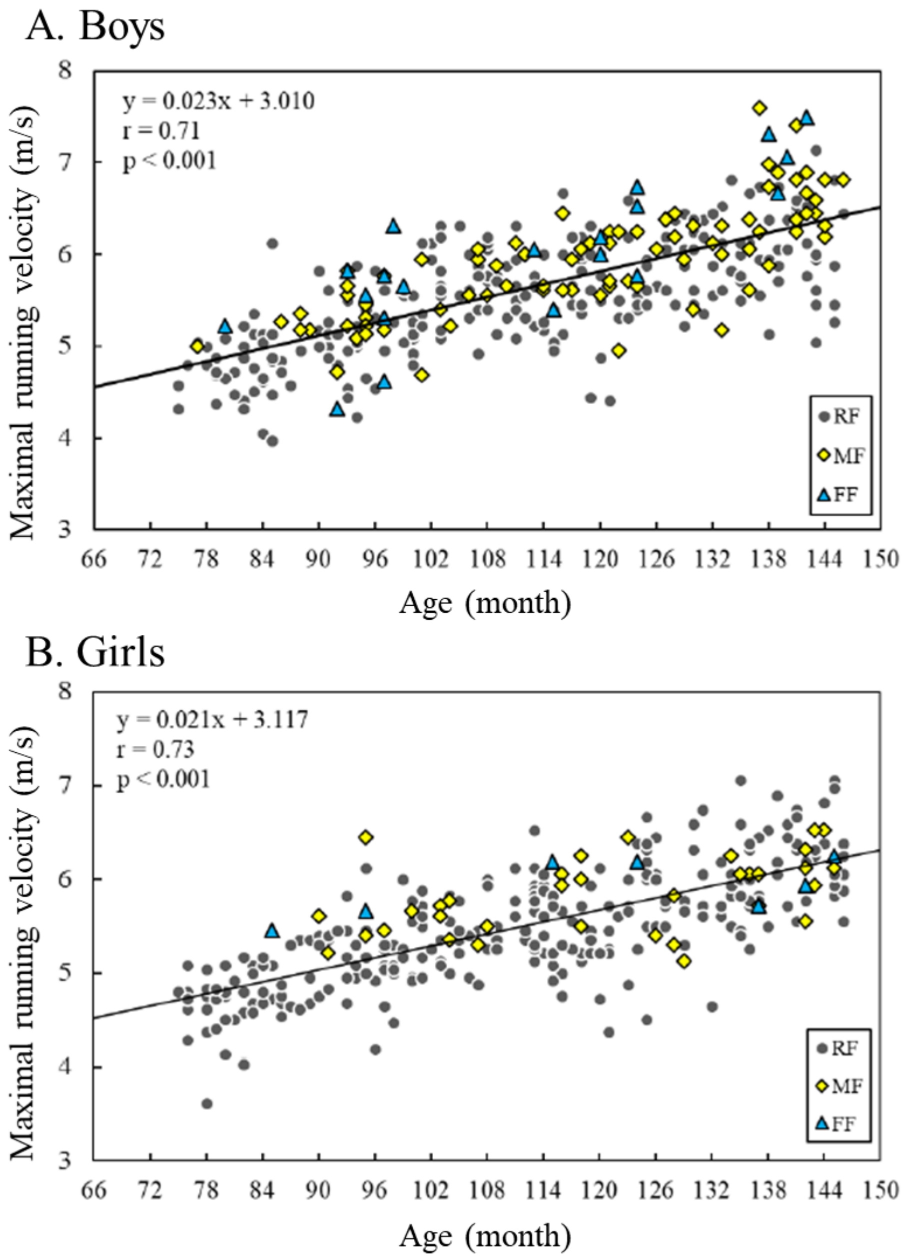

Figure 4-4. Relationship between the age in months and the maximum velocity in boys (A) and girls (B). Rearfoot strike pattern (RF) ， Midfoot strike pattern (MF) ， Forefoot strike pattern (FF) (adapted from Nobuoka et al., 2020)

Chapter 5

General Discussion

The purpose of this thesis was to clarify 1) how the inflection point in V-C-S relationship is influenced with running training (chapter 2), 2) how the V-C-S characteristics changes with growth and development (chapter 3), 3) the relationship between foot strike patterns and sprint performance in preschool children (chapter 4).

In Chapter 2, I investigated spatiotemporal adjustment between step length and cadence in a wide range of running velocity from the minimum to the maximum in subjects with different histories of engagement in running training. The critical point ("inflection point") was obtained at which the relative contribution between cadence and step length to running velocity changes. It was found that the relative running velocity of cadence and maximal running velocity at the inflection point was hardly affected by the training level and the athletic modality.

In Chapter 3, I investigated the spatiotemporal adjustment of running in children ranging from 1 to 12 years. Adult-like inflection point characteristics were observed more often in children of the ages of 10 and 12 than younger ones. On the other hand, the inflection point was not observed in most subjects in children aged 1-6 years, and running velocity modulation was done only with changes in cadence. It was suggested that the inflection point reported in Chapter 2 might occur at a specific stage of growth and development (secondary sexual characteristics period).

In Chapter 4, I clarified the relationship between foot strike patterns and sprint performance in preschool children ranging from 3 to 6 years. In preschool children, as has been reported for elementary school children and adults, the rearfoot strike pattern was the most common ground contact type. For preschool children, the maximum sprinting velocity was not affected by differences in foot strike patterns. Differences in foot strike pattern significantly influenced ground contact time, which contributes to cadence. However, it was suggested that differences in foot strike pattern in preschool children may have only a little effect on sprint performance due to insufficient development of muscle strength and stiffness.

5-1. Inflection point of the V-C-S relationship

The inflection point of the V-C-S relationship is caused by the change in the relative contribution of cadence and step length with the change in running velocity. At low running velocities, step length increases, and at high running velocities, cadence increases (Cavagna et al., 1988; Cavagna et al., 1991; Dillman, 1975; J. Hay, 2002; Hunter et al., 2004; Kaneko, 1990; Luhtanen & Komi, 1978; Nummela et al., 2007; Salo et al., 2011; Weyand et al., 2000). Based on previous studies, the running velocity at which these relationships switch has been considered to be 7 m/s (Dorn et al., 2012; Luhtanen & Komi, 1978; Weyand et al., 2000). In Chapter 2, the inflection point was calculated for subjects with various training backgrounds related to running. The results showed that the inflection point occurred at a lower velocity (mean ± SD: 5.18 ± 0.75 m/s, range: 2.56 - 6.65 m/s, overall) than the inflection points reported in previous studies. This difference may be due to the increased number of velocities analyzed, leading to a more distinct location of the inflection points. In addition, use of the segmented regression method, based on two linear regression lines on a subject-by-subject basis, likely provided a more precise (or different) result in comparison with results based on the polynomial approximation technique (Martin, 2000). Also, the results may have been influenced by the lower maximal running velocities seen in groups of active athletes and sedentary, who had no formal running training and/or did little running. The previous studies focused mainly on athletes who underwent running-specific training. Although the basic characteristics of the V-C-S relationship are common across different subject groups (Chapter 2), the quantitative difference could be related to qualitative/quantitative difference in running-specific training among groups.

It became apparent, however, that the basic properties of this fundamental V-C-S relationship vary across developmental stages (chapter 3). It seems that the characteristics of the V-C-S relationship can be differentiated among several developmental stages. First, the adult-like V-C-S relationship measured in chapter 2 was observed in most children between about 10 and 12 years of age. In this age group, the inflection point was observed in more than 80% of the children (Table 3-1, Figure 3-7). This age group corresponds to the secondary sexual characteristics period. It is unclear whether the participating subjects were beyond the secondary sexual period. In order to determine when this begins, it is useful to measure height longitudinally and calculate the peak height velocity age (PHVA) (Malina et al., 1995). It, however, is possible that various physical changes during this period may have affected the basic characteristics of the V-C-S relationship. There are Individual and gender differences in the timing of secondary sexual characteristics. Therefore, it is possible that subjects younger than ten years old also had inflection points (Table 3-1). In addition, the age group of 7 to 12 years, for which the inflection point was obtained, corresponds to the first to sixth grade of elementary school. Their exercise or sports habits may have influenced the present results. Indeed, some of the participants were involved in sports clubs other than athletics (mainly basketball and soccer). These workouts may have triggered the acquisition of V-C-S characteristics typically observed in older (10-12 years) children or in adults. No adult-like V-C-S relationship was observed for preschoolers (1-6 years old) (Figure 3-3). In this age group the change in running velocity is produced by a change in cadence accompanied with a constant step length. Since preschoolers do not have the sufficiently developed muscle strength and stiffness to increase the step length, the change in running velocity would be mainly caused by the change in cadence (Schepens et al., 1998). It seems likely that their foot strike pattern may affect the range of cadence change (Chapter 4), but differences in foot strike patterns do not affect the increase in step length.

5-3. What are the determinants of the inflection point of the V-C-S relationship?

The present study measured the V-C-S relationship in subjects with various backgrounds (training level and developmental growth) related to running. The inflection point in V-C-S relationship was obtained in almost all adult subjects. This means that running velocity was increased by increasing step length at low running velocities and cadence at high running velocities. Previous studies have attempted to clarify the determinants of cadence by determining mechanical efficiency (Cavagna et al., 1991; Minetti & Alexander, 1997; Salo et al., 2011; Yanai & Hay, 2004). Those studies have been performed at various running velocities and have reported a difference in efficiency between the freely chosen cadence and the most efficient cadence. Although there are individual differences in the V-C-S relationship (Figs. 2-5, 2-6, 2-7, 2-8) in the lower velocity range, it indicates that the current relationship between cadence and step length is more efficient (less oxygen consumption) for each individual compared to other combinations (cadence and step length).

Spatiotemporal constraints (anatomical and temporal) have been implicated in the changes in the relative contributions of step length and cadence (Yanai & Hay, 2004). Dorn et al. (2012) reported that ankle plantar flexor, soleus, and gastrocnemius activity contributed to running velocity below 7 m/s, while hip flexor, iliopsoas, gluteus maximus, and hamstrings activity contributed to running velocity above 7 m/s. This is because the spatiotemporal constraints resulted in greater activity of the muscles contributing to the increase in each spatiotemporal variable. This indicates that the contribution of muscle activity pattern may have also changed at running velocity below and above the inflection point in this study. In other words, it may be possible to infer the individual-specific pattern of muscle activity at a specific running velocity from the individual's V-C-S relationship. Muscle synergy analysis has reported muscle activity patterns of multiple muscles to change with running speed (speed-dependency) (Santuz et al., 2020; Yokoyama et al., 2016; Yokoyama et al., 2017). For example, rectus femoris muscle activity during the swing phase is not observed at lower running velocity. However, the rectus femoris muscle activity increases in the early swing phase as the running velocity increases. Muscle synergy analysis has also reported that neural control is altered during "mode" transitions, such as walk-run (Hagio et al., 2015). The point at which mode transitions occur can be modified by various factors, including metabolic efficiency, pendular dynamics, and excessive use of specific muscles. Another type of transition is one that occurs in the same gait mode, such as "slow swim" and "burst swim" (Budick & O'Malley, 2000). Such changes are referred to as “repertoires” within one gate mode. In this study, the inflection point that was examined could be considered as a transition between different repertoires of running. Inter-group differences were not found in the cadence at the inflection point and the value was constant (overall mean: 3.0 ± 0.1 steps/s) among the subject groups (chapter 2). This result suggests that humans adopt another motor strategies when they reach the cadence at the inflection point. Interestingly, increased activity of spinal interneurons involved with locomotor mechanisms is closely linked to the appearance of locomotor behaviors linked with specific movement frequencies (Talpalar et al., 2013). This has been demonstrated in both larval zebrafish (Ampatzis et al., 2014; Ausborn et al., 2012; Budick & O'Malley, 2000; McLean et al., 2008) and mice (Talpalar et al., 2013; Zhong et al., 2011).

These findings suggest that in human running, too, at specific motor frequencies (cadences), the responsible neural mechanisms may be at work to shift the repertoire at inflection points. Interestingly, the cadence at the inflection point (3 steps/s) coincides with the preferred pedaling cadence (90-100 rpm), which is often used in bicycle road racing (Chavarren & Calbet, 1999; Hagio et al., 2015; Lucía et al., 2001; Takaishi et al., 1998; Takaishi et al., 1996). In bicycle road racing, one of the strategies is to maintain a constant cadence (about 90-100 rpm = 3 steps/s). It is desirable to ride around that cadence from the viewpoint of efficiency. This movement frequency (e.g., 3 steps/s in the running) might be any trigger for cyclic movement in humans. However, since the inflection point may not be observed in some children during their developmental stages, sufficient development may be required for the neural mechanism of this inflection point to appear.

Various changes occur during the transition from preschool to the age of secondary sexual characteristics. It includes the development of bone tissue, such as height and leg length, and the development of muscle and tendon tissue (including, of course, an increase in body mass). However, after the age of 13, an apparent increase in the above parameters has been reported due to secondary sexual characteristics (金子, 1974; 首都大学東京, 2007). Some physical changes may be necessary for the onset of the inflection point of the V-C-S relationship, but it is unclear which parameters are responsible for this. What is important may not be the onset of secondary sexual characteristics, but rather that each parameter reaches a specific criterion (threshold). This quantification would be an important measurement for future studies. If those thresholds can be quantified, it may be possible to develop an appropriate running ability consistent with the developmental stage. In general, it has been reported that the characteristics of running form during sprinting do not change significantly during elementary school (宮丸, 2001). However, when focusing on the inflection point of the V-C-S relationship as in the present study, the running characteristics change even in this narrow age group. The inflection point of the VCS relationship in this study has the potential to provide useful information for talent identification, training method suggestions, or teaching methods in educational settings by evaluating the running ability of each individual.

5-4. Limitations

In this study, we calculated the inflection points by measuring the V-C-S relationship of people from different backgrounds. However, the determinants of the various parameters measured are unknown from the indices used in this study. In particular, the mechanism of the inflection point is very interesting. In the future, motion analysis together with measurements of muscle activity and ground reaction forces could help to answer our overall question. Although numerical simulation of running and walking has many limitations (Minetti & Alexander, 1997; Minetti & Saibene, 1992; Yanai & Hay, 2004), the differences in the V-C-S relationship could be analyzed with numerical models in terms of various energy costs. Furthermore, it is very interesting that even in the sedentary subjects, the basic pattern of V-C-S relationship, which is considered to reflect efficiency (Peyre-Tartaruga & Coertjens, 2018; Yanai & Hay, 2004), was seen. Is the V-C-S pattern innate or does it develop along the development? At the least, it is certain that the properties of the inflection point are influenced by growth and development. Different age groups (teenagers) and longitudinal measurements will be needed to clarify this effect in more detail. Furthermore, the impact of artificial manipulation of these V-C-S relationships (training interventions) is very important. These findings are expected to be useful in teaching running form to children during their developmental period. In addition, also fatigue (Fischer et al., 2015), aging (Cavagna et al., 2008; Pantoja et al., 2016), and sex differences (Stiffler-Joachim et al., 2020), if any, are topics that merit future analysis.

Chapter 6

Conclusion

My doctoral dissertation evaluated the adjustment of spatiotemporal variables in human running by calculating the inflection points in the V-C-S relationships at which the relative contributions of cadence and step length change. The inflection points of spatiotemporal variables during human running show the following characteristics.

(1) At the inflection point velocity of spatiotemporal variables, the relative contribution of each variable begins to change when the cadence reaches about 3 steps/s. This determinant is unaffected by maximal running velocity or physical characteristics.

(2) Inflection points appear around the time of secondary sexual characteristics (10-12 years old). In children aged 1 to 6 years, the inflection point was rarely observed probably due to insufficient muscle strength and stiffness development to increase step length.

The results suggest that training level and athletic modality affect maximal running velocity and running velocity at the inflection point, but cadence at the inflection point may be unique to specific human control mechanisms and development of musculoskeletal system.

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