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| RESEARCH ARTICLE

Motor Performance and 2D:4D Digit Ratio in Male Cross-Country Skiers

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| ABSTRACT
The second-to-fourth digit ratio (2D:4D) is considered a biomarker of prenatal androgen exposure and has been linked to various physical and athletic attributes. However, evidence regarding its relationship with sport-specific motor performance, particularly in endurance-based disciplines, remains inconclusive. The aim of this study is to investigate the relationship between the right-hand 2D:4D digit ratio and selected motor performance parameters-including strength, speed, agility, and endurance-in male cross-country skiers. This cross-sectional study investigated the associations between the 2D:4D digit ratio and multiple performance parameters in male cross-country skiers (n = 15). Anthropometric measurements, 2D:4D ratios (right hand), and performance tests-including 20 m sprint, Illinois agility test, vertical jump, sit-ups, handgrip, and back strength-were conducted under standardized conditions. Pearson correlation analyses were used to examine associations between digit ratio and performance variables. Negative but non-significant correlations were found between the 2D:4D ratio and sprint as well as agility performance, suggesting that lower ratios may be associated with faster and more agile movement patterns. Conversely, a significant positive relationship was observed between 2D:4D and back strength, while other strength measures (handgrip, vertical jump) showed weak positive trends. These findings indicate that in cross-country skiing, which emphasizes endurance, coordination, and trunk stabilization, training-induced neuromuscular adaptations may outweigh the effects of prenatal androgen exposure. The results suggest that the 2D:4D ratio reflects an interaction between biological predisposition and sport-specific training adaptation, rather than serving as an independent determinant of performance. While a lower 2D:4D ratio appears advantageous for speed and agility, the relationship between digit ratio and strength performance may vary depending on the technical and endurance demands of the sport. Future longitudinal studies incorporating hormonal profiling and bilateral digit measurements are needed to clarify whether the 2D:4D ratio can function as a practical biomarker for talent identification and performance monitoring in elite athletes.

| KEYWORDS

2D:4D digit ratio, prenatal androgens, motor performance, agility, strength, cross-country skiing, adolescent athletes

| ARTICLE INFORMATION

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1. INTRODUCTION

The second-to-fourth digit ratio (2D:4D)-that is, the length of the index (2D) finger relative to the ring (4D) finger-has been proposed as an indirect correlate of prenatal androgen exposure, since fetal testosterone and estrogen levels are thought to influence digit development (Kim, 2016; Pasanen et al., 2022). Research shows that once established, the 2D:4D ratio remains relatively stable across development, making it a potentially useful anthropometric marker in adult athletic populations (Pasanen et al., 2022; Gower et al., 2025). Several studies have found that lower 2D:4D ratios are associated with better outcomes in measures of muscular strength and fitness, such as handgrip strength and vertical jump, though the magnitude of these associations tends to be small to moderate (Pasanen et al., 2022).

Across a variety of sports disciplines, the 2D:4D digit ratio has been investigated as a potential correlate of physical performance. Several studies have reported that lower 2D:4D ratios are modestly associated with superior outcomes in speed-, power-, and strength-based activities, such as sprint running, vertical jumping, and handgrip strength (Pasanen et al., 2022; Crewther et al., 2022). Similar findings have been observed in endurance sports, where lower ratios have been linked to higher maximal oxygen uptake (VO_2max) and better running economy, although the evidence remains inconsistent (Holzapfel et al., 2016). A recent meta-analysis suggests that, although effect sizes are generally small, the relationship between 2D:4D and athletic performance is statistically reliable, highlighting the potential relevance of this anthropometric marker for understanding sport-specific capacities (Hönekopp & Schuster, 2010).

Although these findings suggest that 2D:4D may be linked to general strength and endurance capacities, its association with specific motor performance attributes relevant to cross-country skiing remains poorly understood. Cross-country skiing performance relies on a complex interplay of aerobic power, anaerobic capacity, upper- and lower-body strength, trunk stability, and technical efficiency (Sandbakk & Holmberg, 2017; Losnegard, 2019). Several studies have demonstrated that trunk extensor strength and core stability are strongly related to skiing economy and double-poling efficiency, highlighting the importance of these physical qualities for competitive success (Stöggl & Holmberg, 2016; Therell et al., 2022). Despite this evidence, no study to date has directly examined whether the 2D:4D digit ratio is associated with discrete motor components such as back strength, sprint speed, agility, or muscular endurance in cross-country skiing athletes. Addressing this gap may provide sport-specific insights into the developmental and physiological factors that contribute to performance in endurance-power sports.

Based on the evidence that 2D:4D may be linked to general strength- and endurance-related traits, and given the central role of trunk strength, sprint ability, and coordination in cross-country skiing performance, this study aimed to examine the association between right-hand 2D:4D digit ratio and a set of selected motor performance variables in male cross-country skiers. Specifically, we investigated correlations between 2D:4D and back strength, sprint speed, vertical jump performance, agility, sit-up count, and handgrip strength. It was hypothesized that lower 2D:4D ratios would be associated with superior outcomes in strength and power related tests, consistent with findings from other sports.

2. MATERIALS AND METHODS

Participants

Fifteen male cross-country skiers voluntarily participated in this study. Participants were aged between 14 and 16 years and had been actively training and competing in regional or national events for at least three consecutive seasons. All athletes were free from any musculoskeletal injuries, chronic illnesses, or conditions that could influence performance outcomes. They were also not taking any medications known to affect growth, hormonal balance, or neuromuscular function.

Before data collection, participants and their legal guardians received verbal and written explanations about the study aims, procedures, and potential risks. Written informed consent was obtained from both the athletes and their guardians. The study was conducted in accordance with the ethical standards of the Declaration of Helsinki and was approved by the Muş Alparslan University Institutional Research Ethics Committee (Approval No: 214592).

Study Design

This research was conducted as a cross-sectional observational study aiming to investigate the association between right-hand 2D:4D digit ratio and selected motor performance parameters in male cross-country skiers. All measurements were carried out within a single testing session under standardized laboratory and gymnasium conditions to minimize environmental variability. The testing protocol was scheduled in the morning hours (between 09:00 and 11:00 a.m.) to reduce the potential influence of circadian fluctuations on performance outcomes.

Participants first underwent anthropometric assessments followed by digit ratio measurements. Subsequently, a standardized warm-up protocol was completed before performing the motor performance tests in a fixed order to ensure consistency across subjects. Adequate rest intervals were provided between tests to avoid fatigue-related performance decrements.

Anthropometric Assessments

Stature was measured to the nearest 0.1 cm using a wall-mounted stadiometer, and body mass was assessed with a calibrated digital scale while participants were barefoot and wearing light sports clothing. Body mass index (BMI) was calculated as body mass divided by squared stature (kg/m^2). All measurements were performed in duplicate, and the mean value was used for analysis.

2D:4D Measurement

The lengths of the second (index) and fourth (ring) fingers of the right hand were measured using a precision digital caliper. Measurements were taken from the basal crease at the metacarpophalangeal joint to the fingertip with the hand placed flat and fully extended. Two measurements were recorded for each finger, and the mean value was used for analysis. The 2D:4D ratio was calculated by dividing the length of the second digit by the length of the fourth digit.

Motor Performance Tests

Participants completed a standardized warm-up prior to testing. The following tests were performed in a fixed order with adequate rest intervals to minimize fatigue effects:

20 m Sprint: Timed using electronic photocell gates to assess straight-line sprint performance.

Vertical Jump: Measured using a jump mat system to determine explosive lower-body power.

Illinois Agility Test: Conducted according to standard protocols to evaluate change-of-direction ability.

Back Strength: Assessed using an isometric back dynamometer, with participants performing a maximal static pull in a standardized posture.

Sit-Ups: Maximum number of correctly performed repetitions within one minute recorded as an indicator of trunk muscular endurance.

Handgrip Strength: Measured bilaterally with a hand dynamometer; the highest value from two trials for each hand was used for analysis.

All tests were performed on the same day under controlled indoor conditions (temperature 22-24 °C), and participants were instructed to maintain their habitual diet and refrain from strenuous exercise for at least 24 hours prior to testing.

Statistical Analysis

Data were analyzed using IBM SPSS Statistics (Version 22, IBM Corp., Armonk, NY, USA). The normality of all variables was verified with the Shapiro-Wilk test. As the data met normal distribution assumptions, Pearson's product-moment correlation coefficients (r) were calculated to examine associations between right-hand 2D:4D digit ratio and motor performance variables. Statistical significance was accepted at $p < 0.05$.

3. RESULTS

The descriptive characteristics of the participants are summarized in Table 1. The correlation analysis results between right-hand 2D:4D digit ratio and selected motor performance variables are presented in Table 2. The corresponding correlation coefficients are visually illustrated in Figure 1.

Table 1. Descriptive Characteristics of Participants (n = 15)

Variable	Mean ± SD	Min	Max
Age (y)	14.8 ± 0.94	14.0	16.0
Body Mass (kg)	53.97 ± 9.48	40.6	77.1
Stature (cm)	166.07 ± 10.41	150.0	185.0
BMI (kg/m^2)	19.45 ± 1.78	16.77	23.28

Values are presented as mean ± standard deviation (SD) with minimum and maximum range.

Table 2. Pearson's correlation coefficients (r) and p-values between right-hand 2D:4D digit ratio and motor performance variables in male cross-country skiers (n = 15).

Variable	r	p
20 m Sprint	-0.503	0.056
Vertical Jump	0.407	0.132
Illinois Agility Test	-0.322	0.242
Back Strength	0.532	0.041*
Sit-ups	0.047	0.868
Handgrip Strength (Right)	0.381	0.161
Handgrip Strength (Left)	0.197	0.482

Values represent bivariate correlations. *p < 0.05 indicates statistical significance.

Pearson's correlation coefficients (r) and p-values between the right-hand 2D/4D digit ratio and selected performance parameters in male athletes. A significant positive correlation was found with back strength (r = 0.532, p = 0.041). Negative trends were observed with 20 m sprint (r = –0.503, p = 0.056), while associations with vertical jump, Illinois agility test, sit-ups, and handgrip strength (right/left) remained weak to moderate and did not reach statistical significance (p > 0.05).

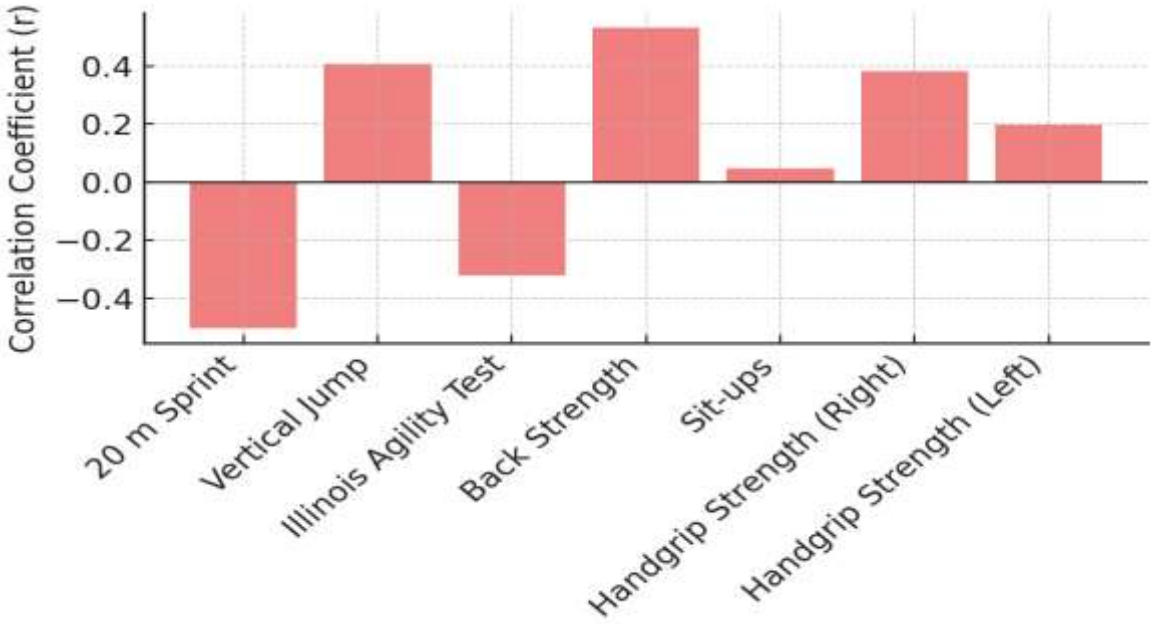

Fig. 1 Pearson's correlation coefficients (r) between right-hand 2D:4D digit ratio and motor performance variables in male cross-country skiers.

Positive and negative associations are represented by upward and downward bars, respectively. A significant correlation was observed only for back strength (p < 0.05), while other parameters demonstrated non-significant trends.

4. DİSCUSSİON AND CONCLUSİON

In the present study, the negative correlations observed between the 2D:4D digit ratio and both sprint and agility performance in male cross-country skiers, although not statistically significant, are generally consistent with previous findings reporting that lower 2D:4D ratios are associated with superior motor performance. Since shorter completion times in time-based tests (e.g., the 20-m sprint and Illinois agility test) reflect better performance, the negative correlation coefficients can be interpreted to mean that as the 2D:4D ratio decreases, speed and change-of-direction ability tend to improve. This pattern aligns with earlier evidence emphasizing the organizational effects of prenatal testosterone exposure on neuromuscular coordination, reaction time, and force-production capacity (Crewther et al., 2022; Hönekopp & Schuster, 2010; Pasanen et al., 2022). Although statistical significance was not reached in the current sample, the direction of these associations conforms to both biological and theoretical expectations reported in the literature. Given the limited sample size (n = 15) and the inclusion of adolescent athletes whose endocrine profiles are still developing, it is plausible that these factors attenuated the strength of the observed correlations. Nevertheless, the present results support the notion that the 2D:4D digit ratio may serve as a potential biological marker of speed- and agility-related performance components.

The negative trend observed between the 2D:4D digit ratio and sprint as well as agility performance is most likely underpinned by the long-term neuromuscular effects of prenatal androgen exposure. A higher testosterone-to-estradiol ratio during fetal development may influence central nervous system organization, muscle fiber-type composition, and motor neuron patterning, thereby enhancing an individual's potential for greater speed, reaction sensitivity, and muscular power output (Manning & Fink, 2008; Hönekopp et al., 2007). Together with differences in androgen receptor density, these developmental effects may increase the proportion of type II fast-twitch muscle fibers, providing a functional advantage in activities that demand rapid force production such as sprinting and agility tasks (Folland et al., 2012). Furthermore, individuals with lower 2D:4D ratios have been shown to exhibit higher levels of competitiveness, motivation, and risk-taking propensity (Kilduff et al., 2011). These psychobiological traits, when integrated with rapid decision-making and directional change capabilities, may collectively enhance agility performance under sport-specific conditions.

In the present sample, which consisted of adolescents assessed during the pubertal period, the ongoing developmental fluctuations in testosterone levels may have attenuated the strength of the associations between the 2D:4D ratio and performance variables. Nevertheless, previous research has consistently demonstrated that a lower 2D:4D ratio is positively associated with sprint (Manning & Hill, 2009), agility (Bennett et al., 2010), and explosive power (Crewther et al., 2022) performances. These findings lend support to the biological relevance of the negative but nonsignificant correlations observed in the current study. Thus, the present results suggest that the 2D:4D ratio may represent an early biological marker of speed- and agility-related components; however, confirming this relationship with greater precision will require larger samples and longitudinal studies incorporating hormonal profiling across developmental stages.

When strength-related performance variables were examined, a positive and significant correlation was found between the 2D:4D ratio and back strength, whereas positive but nonsignificant tendencies were observed for vertical jump and handgrip strength. This pattern partially contradicts the general consensus in the literature indicating that a lower 2D:4D ratio is typically associated with higher muscular strength (Folland et al., 2012; Pasanen et al., 2022). In particular, the positive relationship between the 2D:4D ratio and back strength runs counter to the frequently reported trend whereby lower 2D:4D values correspond to greater strength capacities. One plausible explanation is that the back strength test primarily evaluates the isometric capacity of proximal muscle groups (trunk extensors), whereas associations between 2D:4D and muscular performance are more often evident in distal or explosive strength measures such as handgrip, sprint, or vertical jump (Bennett et al., 2010; Crewther et al., 2022).

Moreover, lower 2D:4D ratios have been genetically associated with greater androgen receptor sensitivity and, consequently, a higher myogenic capacity (Manning & Fink, 2008; Hönekopp et al., 2007). However, long-term endurance and resistance training can enhance neuromuscular coordination and core stabilization independently of hormonal sensitivity, potentially masking the effects of innate biological differences. In technically demanding disciplines such as cross-country skiing, core strength and postural stability are among the primary determinants of performance (Sandbakk & Holmberg, 2017). Therefore, the positive relationship observed between the 2D:4D ratio and back strength in this study is more plausibly explained by neuromuscular adaptations induced by training, rather than by androgen-related biological effects.

The weak positive tendencies found between the 2D:4D ratio and both sit-up and vertical jump performance further support this interpretation, as these tests primarily reflect muscular endurance and core control rather than explosive or maximal force production. Previous studies reporting significant associations between lower 2D:4D ratios and higher anaerobic power

outputs-such as in Wingate or vertical jump performance (Kilduff et al., 2011; Crewther et al., 2022)-were typically conducted among adult or elite athletes. In contrast, the adolescent participants in the present study may differ in both hormonal maturation and the endurance-oriented development of trunk musculature. Collectively, these findings suggest that, in strength-related parameters, the direction and magnitude of associations with 2D:4D may vary depending on sport discipline, age, and training background. Consequently, the 2D:4D ratio alone may represent a limited predictor of muscular strength performance in adolescent endurance athletes.

Cross-country skiing is a comprehensive sport that requires a high level of development in both aerobic endurance and neuromuscular strength components. Performance in this discipline depends not only on cardiorespiratory capacity but also on core stability, upper and lower limb coordination, force transmission, and technical efficiency (Losnegard, 2019; Sandbakk & Holmberg, 2017). The positive relationship observed between the 2D:4D ratio and back strength may therefore carry a different implication when interpreted within the specific demands of this sport. The back extensor muscles play a crucial role in force generation and postural control during key movement phases such as double poling and uphill propulsion. Consequently, the higher 2D:4D ratios observed among athletes with greater back strength are likely to reflect the dominant influence of training-induced adaptations on core strength development, rather than the direct effects of prenatal androgen exposure. In other words, in cross-country skiing, technical proficiency and sustained strength endurance may exert a stronger impact on performance than congenital hormonal indicators.

Furthermore, because cross-country skiers typically maintain high training volumes, prolonged endurance-based exercise has been shown to induce regulatory adjustments within the hypothalamic-pituitary-gonadal axis, occasionally resulting in transient reductions in circulating testosterone levels (Hackney, 2001). Such adaptations may alter the influence of prenatal androgenic signals through epigenetic mechanisms or training-mediated hormonal modulation. Therefore, the weak and variable correlations observed between the 2D:4D ratio and motor performance parameters in this study may, at least in part, be explained by the endocrine adjustments elicited by chronic endurance training that reshape hormonal balance over time.

In conclusion, the findings of the present study revealed negative trends in sprint and agility performance that align with the existing literature, alongside a sport-specific positive association between the 2D:4D ratio and back strength. These results suggest that the 2D:4D ratio should not be regarded as an isolated determinant of performance but rather as an indicator reflecting the interaction between biological predispositions and training-induced adaptations. While a lower 2D:4D ratio appears to favor neuromuscular qualities such as speed, agility, and reactive power, the direction and magnitude of this association may become more complex in technically demanding and endurance-based sports such as cross-country skiing, where performance relies heavily on core stability and technical efficiency.

Future research should aim to investigate both right- and left-hand digit ratios across athletes of different ages and performance levels, while simultaneously incorporating hormonal profiling and detailed training histories. Longitudinal designs will be particularly valuable in elucidating how 2D:4D interacts with sport-specific performance determinants over time. Such studies could help refine the interpretation of the 2D:4D ratio from a broad biological marker of developmental potential to a practical biomarker applicable in talent identification, performance monitoring, and athlete development frameworks.

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