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Dear Esteemed Readers, Authors, and Reviewers,

We are delighted to present this edition of Montenegrin Journal of Sports Science and Medicine, featuring ten articles that represent the forefront of our scientific field. These contributions, ranging from sport medicine, biomechanics, training effects, offer fresh perspectives and significant advancements, reflecting the dynamic nature of sport sciences. Each paper has undergone rigorous peer review, ensuring the highest standards of scientific rigor and originality.

This collection arrives at an exciting juncture, as we prepare to convene in the picturesque town of Cavtat, Croatia, for our upcoming conference organized by Montenegrin Sports Academy and partner faculties, in early April. The vibrant atmosphere of Cavtat, with its rich history and stunning Adriatic coastline, and fantastic venue of Hotel Croatia, will provide an ideal setting for intellectual exchange and collaboration. We anticipate that the discussions sparked by these articles will continue and deepen during the conference, fostering new insights and partnerships.

We extend our sincere gratitude to the authors for their insightful contributions, and the reviewers for their invaluable feedback.

Warm regards,
Prof. dr. Dusko Bjelica
Prof. dr. Damir Sekulic

ORIGINAL SCIENTIFIC PAPER

Intersexual Differences and Relationship of Specific and General Muscle Strength of Young Sports Climbers

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Abstract

Climbers benefit from a combination of general and specific strengths, which are tailored to meet the demands of climbing. The aim of the study is to assess the intersexual differences of general and specific muscle strength and the gender-specific relations between specific and general muscle strength of youth boulderers. The research sample consisted of 26 young climbers divided into two groups according to gender. To assess general muscle strength climbers performed hand dynamometry, bent- arm hang and hang on bar. From the viewpoint of assessing specific muscle strength, testing included maximal flexor-finger strength test, bent-arm hang on hangboard, finger hang test. The intersexual differences were evaluated by Mann-Whitney U test, while the relationships between general and specific muscle strength were evaluated by Spearman's rank correlation coefficient. The correlation analysis of boys muscle strength showed statistically significant relationship between the relative strength of the hand grip and maximum finger strength ($p<0.05$; $r=0.58$) and also strength endurance of back and forearm muscles ($p<0.01$; $r=0.73$). Statistically significant relationship between general and specific strength endurance of back and forearm muscles was proven for girls muscle strength ($p<0.01$; $r=0.87$). The findings suggest that appropriate assessment of specific and general muscle strength could serve as a tool for sport-specific selection.

Keywords: *climbing, sport-specific tests, young athletes, strength parameters*

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Introduction

With the growing popularity of sport climbing, more and more young people are taking up this sport at a very young age, while currently organized training starts at the age of around 5 years, which has caused that incoming generations are getting into sports climbing younger than ever (Kozina et al., 2016). In the last few decades the most talented climbers have been relatively young. The 2019 female World senior climbing medalist

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were aged 15 years, an age that can also found among adult World cups competitors. Data of young climbers are rare but currently, there are few researches that deal with fitness profiling (Gilič,Vrdoliak 2023; Vrdoliak, Gilič and Skontic 2022), physiological responses (Morrison and Schöffl 2007) and tactical and psychological training models of young sports climbers (Trifu, Stănescu, and Pelin, 2021).

From the point of view of the structure of sports performance in climbing, strength plays a crucial role in a climber's performance, encompassing both general and specific strength attributes. General muscle strength refers to overall muscular capability, including the strength of large muscle groups used in a variety of movements, not limited to climbing. España-Romero et al. (2010) highlighted the importance of general strength training for climbers, noting that core and upper body strength contribute significantly to overall climbing performance, even if not directly tailored to climbing movements. Watts et al. (2008) identified general fitness parameters, including aerobic capacity and muscle endurance, as foundational to climbing performance, suggesting that while not specific, these aspects are still crucial for overall athletic conditioning.

Specific muscle strength in climbers refers to strength that is directly applicable to the unique demands of climbing. Mermier et al. (2000) demonstrated that while general strength attributes contribute to climbing, specific strength metrics, like grip strength and finger endurance, are more directly correlated with climbing success, particularly in difficult routes and bouldering problems. The maximum strength and muscle endurance of the finger flexors are considered the main determinants (Assmann et al., 2021; Laffaye, Levernier and Collin, 2016). It requires repeated isometric contractions of the finger flexors, the intensity and duration of which vary depending on the size and composition of the "hold" that the climber is grasping and the movements he is performing (Amca et al., 2012).The most frequently used test of maximum isometric strength of the forearm muscles in climbing research is hand dynamometry (Gilič, Vrdoliak 2023; Cheung et al., 2011; Michailov et al., 2015). The reliability of this test has been repeatedly verified in different populations (España-Romero et al., 2010; Schetman, Gestewitz, Kimble, 2005).The finger hang test is also often used, which mainly reflects the strength endurance of the finger flexors (Kodejška and Balaš 2016). It turned out that this test has a very strong relationship with RP performance in both women and men (Balaš et al., 2012).

The endurance of shoulder girdle muscle is also connected with climbing success (MacKenzie et al., 2020). According to several authors (Balaš et al., 2012; Draper et al. 2021; Kalayci and Baskan 2023; Michailov at al. 2018) a higher strength of the shoulder girdle and finger flexors is associated with an increase climbing performance, which caused the creation of a number of climbing tests. Bent-arm hang is one of the general tests and was taken over to climbing. The test focuses on the strength and endurance requirements of the upper limbs and shoulder girdle (Kodejška and Balaš 2016).

Mermier et al. (2000) demonstrated that while general strength attributes contribute to climbing, specific strength metrics, like grip strength and finger endurance, are more directly correlated with climbing success, particularly in difficult routes and bouldering problems.

In order to optimize climbing performance, it is also necessary to focus on the sex differences that this sport brings. Gender differences in sports climbing can be observed in various aspects such as physical attributes, performance, participation rates, and competitive dynamics. Generally, male climbers have higher upper body strength and greater muscle mass, which can give them an advantage in routes that require powerful moves or dynamic movements (Mermier et al 2000; Grant et al. 2001). Female climbers often have better flexibility and a lower center of gravity, which can benefit them on routes that require balance, precision, and technical skill. They may excel in technical routes that emphasize technique over raw power (Watts et al. 2003).Bouldering is a discipline which requires short bursts of power and strength. Men typically excel due to their upper body strength, but women often perform well on problems that prioritize technique and flexibility (Draper et al. 2011).The study by Baláš et al. (2012) also indicates that there are differences in the structure of sports performance between genders. However, there is a lack of studies investigating gender differences in young climbers. The study of Vrdoliak, Gilič and Skontic (2022) confirmed that there are differences in body composition between the sexes, however no gender difference in the applied sport-specific tests of conditioning capacities was found. Another study of Gilič and Vrdoliak (2023) demonstrated associations between forearm capacity in sitting position and maturity offset in girls, but not in boys.

The aim of the study is to assess the intersexual differences of general and specific muscle strength of youth boulderers. Additionally, the aim was to investigate the gender-specific relations between specific and general muscle strength.

Methods

Participants

The research sample consisted of 26 young sports climbers divided into two groups according to gender. The climbing level based on the International Rock Climbing Research Association (IRCRA) reporting scale representing an advanced climbing level for girls and intermediate level for boys. The observed climbers performed the training process twice a week for 90 minutes. The research sample was selected according to following criteria: uninterrupted training process of at least 3 months before inclusion in the research, without injuries, recreational competitor, bouldering as sport discipline. The exclusion criteria were: lead or speed as sport discipline, injuries, no competition achievements. Detailed description of research sample is presented in Table 1.

Participants were instructed to avoid engaging in intense physical activity within 24 hours before the testing session, as well as consuming caffeine within 12 hours previous to the testing session, so order to prevent any possible performance-enhancing effects acording Guest et al.(2021).

Table 1: Description of research sample

Gender	n	Decimal age (years)	Sports age (years)	IRCRA scale	Body height (cm)	Body weight (kg)	BMI (kg/m^2)
		Median±quartile deviation					
Boys	16	14.20±0.96	2.75±1.94	17	168.40±4.16	49.25±5.83	17.55±1.25
Girls	10	12.75±0.78	3.75±0.88	18	155.65±3.31	44.90±6.13	18.20±1.48

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Procedures

The participants were tested during two testing sessions with two day rest between them. At the beginning of the first testing session participants were tested on anthropometric indices. Subsequently, the participants performed warm-up with the trainer consist from 5 minutes general warm-up and 15 minutes specific warm up on the wall where performed 5 minutes of an easy climbing traverse followed by 10 min of progressive bouldering (50–80% of their maximum). During the warm-up boulders, the participants had a minimum of 1-min rest between boulders and ~10 min of rest before testing accoriding to Hermans et al. (2022).

After the warm-up the participants performed 3 general muscle strength tests (hand dynamometry for dominant and non-dominant hand, hang on bar, bent-arm hang) and 3 specific muscle strength test (maximal flexor-finger strength test for dominant and non-dominant hand, finger hang test, bent-arm hang on hangboard). The tests were selected based on available scientific articles, according to the testing methodology of several authors (Draper et al. 2021; Kalayci and Baskan 2023; Michailov at al. 2018; Mermier et al. 2000; Winnick and Short 2014). General tests were performed using hand dynamometer Lafayette 78010 (Lafayette Instrument Company, Lafayette, USA) and bar. Specific tests were performed using a Climbro hangboard (Climbro Ltd., Sofia, Bulgaria) mounted on a vertical hanging platform. Climbro has integrated force sensors (sample rate 100 Hz) and phone application Climbro providing instructions and real-time feedback about force and time of muscle contraction.

Hand dynamometry for dominant and non-dominant hand

The tested person, in standing position grasped hand dynamometer by the dominant hand and gradually exerted the maximum pressure. The pressure was graduated for at least two seconds. After recording the result, the non-dominant hand was measured. During the grip, the outstretched hand was not allowed to touch any part of the body. The movable part of the handle was adjusted to reach the first phalanx of the ring finger. Two attempts were made and the best result for both hands was recorded to the integer number. The relative strength of the hand grip and finger flexors was expressed by the ratio of the climber's absolute strength and weight.

Bent-arm hang

The test is aimed at evaluating muscle endurance of shoulder girdle and back muscles. The tested person tried to hold onto the 2.5 diameter metal bar in the pull-up position, for as long as possible. The grip width matched that of the shoulders. The chin was kept above the bar level. The tested person was taken up to the required position and when person was ready to start the time started. The chin was not allowed to touch the bar during the test. The tested person was verbally supported. The test was finished at the moment when the chin sank under the bar level. The result was measured with accuracy of 0.1 s.

Hang on bar

The test is aimed at evaluating endurance of forearm muscles. The tested person stands under the bar and grabs the bar with both hands. The grip width matched that of the shoulders. After the start signal sounds the tested person hangs onto the bar for as long as possible. The test was finished after the tested person was unable to continue hanging. The test result was recorded with an accuracy of 0.1 seconds.

Maximal flexor-finger strength test for dominant and non-dominant hand

The test is aimed at evaluating the maximum finger strength. The test is performed by applying the maximum force that tested person knows generate with one hand on 2.3 centimeters hold with an open grip. The tested person stands under the hold with arms at approximately 180° shoulder flexion with slightly flexed elbow and knees and grabs the hold with the chosen arm and open grip. After the start signal sounds, the tested person gradually loads the hold by bending the knees but feet are still touching the ground so that he weighs the chosen hand the most. The test person must not „pull" by bending the elbow of chosen arm. The tested person has 5 seconds to load the hold as much as possible. The test ends automatically after two repetitions with each arm. If tested person is able to hang on the hold during the test, an additional load is added.

Bent-arm hang on hangboard

The test is aimed at evaluating shoulder girdle and back muscles and forearm muscles muscular endurance. The tested person tried to hold onto the 30 mm hold in the pull-up position, for as long as possible. The grip width matched that of the shoulders. The chin was kept above the hold level. The tested person was taken up to the required position and when person was ready to start the time started. The chin was not allowed to touch the hold during the test. The tested person was verbally supported. The test was finished when the person was unable to hold onto the rung. The result was measured with accuracy of 0.1 s.

Finger hang test

The test is aimed at evaluating strength endurance of forearm muscles. The test is performed on 30 mm deep edge with 12 mm radius wooden hold. The tested person stands under the hold and grabs the hold with both hands. After the stars signal sounds, the tested person hangs onto the hold for as long as possible. The result was measured with accuracy of 0.1.

Bioethical Committee

All participants were informed about procedures, risks and times of the research and signed the informed consent before initiating the research. Parents or legal guardians signed the informed consent for participants under the age of 18. The study was conducted according the guidelines of the declaration of Helsinki. The research was approved by Ethics Committee of UPJŠ (No. 1/2022).

Statistical analysis

The obtained data were processed by statistical analysis using Statistica 14.1. Based on the low quantity of the research sample ($n<30$) and the results of the assessment of the normality of the data distribution using the Shapiro-Wilk test, non-parametric mathematical and statistical characteristics and tests were chosen for further analysis. The intersexual differences were evaluated based on the results of Mann-Whitney U test at the significance level of $p<0.05$. The coefficient r was used to evaluate the effect size within the Mann-Whitney U test procedure, which was interpreted using the cut-off values as follows: 0.10 ≤r 0.29 – small effect, r = 0.30 ≤r 0.49 – medium effect, r ≥0.50 – large effect. The strength of association between the factors was evaluated based on the results of Spearman's rank correlation coefficient at the significance level of p<0.05 and p<0.01. The results of the correlation coefficients were interpreted according to the scale presented by Cohen (1992): 0.10 ≤r 0.29 –small effect, r =0.30 ≤r 0.49 –medium effect, r ≥0.50 –large effect.

Results

The results of general and specific muscle strength tests of girls and boys together with intersexual differences are presented in Table 2.

Table 2: Intersexual differences of general and specific muscle strength

	Boys (n=16)		Girls (n=10)		Mann-Whitney U			
	Med	QD	Med	QD	U	Z	p	r
HDDH rel	0.60	0.10	0.42	0.08	34.00	-2.42	0.02	0.47†
HDNH rel	0.50	0.09	0.41	0.10	40.00	-2.11	0.04	0.41†
BAH [s]	60.46	18.64	55.36	25.36	5.00	-3.95	<0.01	0.77‡
HB [s]	150.84	27.80	122.81	45.74	43.00	-1.95	0.05	0.38†
MFFST DH rel	0.72	0.08	0.73	0.06	79.00	-0.05	0.96	0.01
MFFST NH rel	0.67	0.06	0.72	0.08	67.00	-0.69	0.49	0.14
BAHHB [s]	24.04	7.83	24.29	15.54	78.00	-0.11	0.92	0.02
FHT [s]	28.19	13.32	35.95	14.79	79.00	-0.05	0.96	0.01

Note. HDDH: hand dynamometry for dominant hand (kg/body weight); HDNH: hand dynamometry for non-dominant hand (kg/body weight); HB: hang on bar; BAH: bent-arm hang; MFFST DH: Maximal flexor-finger strength test for dominant hand (kg/body weight); MFFST NH: Maximal flexor-finger strength test for non-dominant hand (kg/body weight); BAHHB: Bent- arm hang on hangboard; FHT: Finger hang test; Med: median; QD: quartile deviation; U: Mann Whitney U test criterion; Z: critical value for 95% confidence interval; p: statistical significance; r: effect size (0,1 – small; 0,3† – medium; 0,5‡ – large)

An analysis of general muscle strength showed statistically significant differences in the relative strength of the hand grip and muscle endurance of upper limbs in the relation to sex. In comparison to girls, boys achieved a higher level in all tests of general muscle strength. An analysis of specific muscle strength showed no statistically significant differences in relation to sex. Based on a comparison of medians we can conclude a higher level in all tests of specific muscle strength in girls compared to boys (table 2).

Based on the correlation analysis of boys muscle strength,

Table 3: Relationship between general and specific muscle strength of boys climbers

	HDDH rel	HDNH rel	BAH	HB	MFFST DH rel	MFFST NH rel	BAHHB	FHT
HDDH rel	1.00							
HDNH rel	0.90**	1.00						
BAH [s]	0.52*	0.46	1.00					
HB [s]	0.16	0.28	0.34	1.00				
MFFST DH rel	0.58*	0.57*	0.57*	-0.05	1.00			
MFFST NH rel	0.59*	0.49	0.60*	-0.18	0.82**	1.00		
BAHHB [s]	0.73**	0.64**	0.50	0.39	0.29	0.36	1.00	
FHT [s]	0.82**	0.84**	0.61*	0.34	0.59*	0.61*	0.67**	1.00

Note: HDDH: hand dynamometry for dominant hand (kg/body weight); HDNH: hand dynamometry for non-dominant hand (kg/body weight); HB: hang on bar; BAH: bent-arm hang; MFFST DH: maximal flexor-finger strength test for dominant hand (kg/body weight); MFFST NH: maximal flexor-finger strength test for non-dominant hand (kg/body weight); BAHHB: Bent-arm hang on hangboard; FHT: finger hang test; * – p < 0.05; ** – p < 0.01

Table 4: Relationship between general and specific muscle strength of girls climbers

	HDDH rel	HDNH rel	BAH	HB	MFFST DH rel	MFFST NH rel	BAHHB	FHT
HDDH rel	1.00							
HDNH rel	0.83**	1.00						
BAH [s]	0.41	0.23	1.00					
HB [s]	0.52	0.48	0.67*	1.00				
MFFST DH rel	0.29	0.17	0.76*	0.81**	1.00			
MFFST NH rel	0.15	0.16	0.69*	0.61	0.84**	1.00		
BAHHB [s]	0.56	0.50	0.87**	0.90**	0.85**	0.79**	1.00	
FHT [s]	0.51	0.42	0.71*	0.85**	0.79**	0.82**	0.90**	1.00

Note: HDDH: hand dynamometry for dominant hand (kg/body weight); HDNH: hand dynamometry for non-dominant hand (kg/body weight); HB: hang on bar; BAH: bent-arm hang; MFFST DH: maximal flexor-finger strength test for dominant hand (kg/body weight); MFFST NH: maximal flexor-finger strength test for non-dominant hand (kg/body weight); BAHHB: Bent-arm hang on hangboard; FHT: finger hang test; * – p < 0.05; ** – p < 0.01

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we can conclude a statistically significant relationship between the relative strength of the hand grip and maximum finger strength and also strength endurance of back and forearm muscles. It is also possible to observe the occurrence of dependence between muscle endurance in bent-arm hang and maximum finger strength and strength endurance of forearm muscles on hangboard.

Based on the correlation analysis of girls muscle strength, we can conclude a statistically significant relationship between general and specific strength endurance of back and forearm muscles. It is also possible to observe the highest occurrence of dependence between specific strength of fingers and strength endurance of back and forearm muscles on hangboard (table 4).

Discussion

This study aimed to assess gender-specific relations between specific and general muscle strength of youth boulderers and their intersexual differences. Results did reveal differences in studies variables between genders in general muscle strength in favor of boys, who had higher level of general muscle strength in all tests, this may be due to the higher decimal age of the boys, which was 14 years. At this age, there is a sharp increase in muscle strength of boys (Armstrong, Van Mechelen, Ba De Ste Croix 2023). At around 15 years old, many boys are in the midst of or completing puberty, leading to a significant increase in testosterone levels. This hormone promotes muscle growth, especially in the upper body, leading to greater muscle mass and strength development (Rogol et al. 2000; Espen et al. 2011) .

On the opposite, results did not reveal statistically significant differences in studies variables between genders in specific muscle strength, which can be cause due to the higher sports age of the girls. Another reason may be the nature of the structure of sport climbing performance which necessitates the development of specific abilities in comparable manner in both sexes (Vrdoliak, Gilic, Kontic 2022). Potential explanation is the manner in which athletes are selected for participation in sporting activities. In Slovakia, data from the Slovak Mountaineering Association indicate that more girls than boys participated in children's and youth climbing competitions last year. This is related to the observed decline in participants between the U14 and U16 age categories for boys. A similar trend was also confirmed in the research of Emmonds et al. (2021), who also recorded a significant decline in participation for youth males from U14 to U18 in most sports.

The results of correlation analysis of boys muscle strength proved statistically significant relationship between the relative strength of the hand grip and maximum finger strength and also strength endurance of back and forearm muscles, which are important predictors of climbing performance (Baláš et al. 2012; Ginszt et al. 2023). This is also pointed out by the research Kalayci and Baskan (2023) who examined on 52 sports climbers the relationship of anaerobic power, upper extremity strength and competition performances. Significant relationships were found between upper extremity strength values and result of the competition. The factors affecting climbing performance were explained as 65.22% finger and hand grip strength values.

Correlation analysis for girls showed us different results. It was shown that for girls, the bent-arm hang test has a statistically significant relationship with all specific tests, which may mean that the strength of the shoulder girdle may be more important for girls in relation to climbing performance, which was also confirmed in the research of Kodejška and Baláš (2016), who focused on evaluating relationships between the rock climbing performance and the strength of finger flexors and shoulder girdle muscles in female rock climbers.

The hang-on bar test is influenced by the performance of hand dynamometry, as evidenced by the lower correlations observed in boys. This is due to the fact that boys perform better in hand dynamometry, which results in a lower intensity of the hang-on bar test relative to their maximal voluntary strength. Consequently, the hang-on bar test has a greater endurance component in boys than in girls. This can also suggest that the importance of general strength in climbing is overstated, as there are no gender differences in sport-specific tests. Girls compensate for their longer sport-specific age, but the correlations between MFFST and FHT are lower in boys (R=0.59-0.61) than in girls (R =0.79-0.82). Consequently, despite the fact that boys perform the same in MFFST, THT contains more endurance components for boys than for girls, whereas girls have more strength components.

It should be noted that our study has some limitations. Research focused only on boulderes not for lead or speed climbers, therefore it would be appropriate to expand the research to include these two sports disciplines in the future. There was also a certain inhomogeneity of sports age between boys and girls, which could affect the monitored strength parameters. Most research focuses on the adult population, research dealing with youth is rare, so it was difficult to compare the performance level of other youth climbers. But on the other hand, this is the uniqueness of our study together with fact that that is one of the first research on climbers from Slovakia.

Conclusions

Climbers benefit from a combination of general and specific strengths, which are tailored to meet the demands of climbing. General strength constitutes the foundation of overall athleticism, whereas specific strengths directly impact climbing performance by addressing the distinctive physical challenges inherent to the sport. This study assess the intersexual differences and gender-specific relations between specific and general muscle strength of youth boulderers. Results did reveal statistically significant differences in studies variables between genders in general muscle strength in favour of boys. On the other side there are non- existing or negligible gender differences of specific muscle strength which can be caused by selected research sample. Correlations of specific and general muscle strength showed that there were more evident and stronger relationship between specific and general muscle strength among males than in females. In order to design a training programme with the specific aim of developing general and specific muscle strength, it is first necessary to highlight the methods that are typically used to assess training levels. An efficacious training programme for climbers should comprise elements that cultivate both types of strength, thereby ensuring comprehensive development and enhanced climbing ability. The present study may suggest a modification of the training process in sport climbing based on gender, which may have an impact on the development of strength skills among boulderers.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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REVIEW PAPER

The Effectiveness of Cervical Sensorimotor Control Training for the Management of Chronic Neck Pain Disorders: A Systematic Review and Meta-Analysis

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Abstract

This systematic review and meta-analysis aimed to evaluate the effectiveness of cervical sensorimotor control training for the management of chronic neck pain (NP) disorders compared to no treatment, or other conservative or non-conservative treatments. The review was conducted following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines (PROSPERO registration number: CRD42022381714). A comprehensive database search was performed (until November 2023) for randomized controlled trials (RCTs) and clinical trials evaluating the effects of cervical sensorimotor control training on several subjective and objective outcomes in adults with chronic NP (traumatic or non-traumatic origin). Data on study and patient characteristics, outcome measures, and effects on primary and secondary outcomes were extracted. Seven RCTs (409 participants) were included, of which 6 qualified for meta-analysis. Low-certainty evidence suggests that cervical sensorimotor control training is more effective for reducing pain (standardized mean difference (SMD): 0.48; 95% confidence interval (CI): 0.07 to 0.89) and improving cervicocephalic kinesthesia at short term than no treatment, and for reducing kinesiophobia at intermediate term compared to other treatment modalities. No significant between-group differences were found for other outcomes and follow-ups (very low-to-moderate-certainty evidence). Considering the significant improvements in cervicocephalic kinesthesia, cervical sensorimotor control training could be an important element in the rehabilitation of patients with chronic NP disorders. However, the current evidence in the literature is scarce to draw conclusions regarding its effectiveness as a stand-alone rehabilitation program.

Keywords: *chronic neck pain, exercise, meta-analysis, neck kinesthesia, proprioception, sensorimotor control*

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Introduction

Neck pain (NP) is one of the most commonly reported musculoskeletal disorders (Kazeminasab et al., 2022), affecting more than 30% of people annually (Cohen, 2015). It is an important public health concern in the general population (Safiri et al., 2020) that often results in significant disability and economic costs (Hurwitz et al., 2018; Kazeminasab et al., 2022). Patients with NP suffer from pain and discomfort, while also report being limited in their daily activities due to pain-related disability (Nolet et al., 2015). Such functional limitations can affect patients' quality of life, which is often compromised in this population (Lin et al., 2010; Nolet et al., 2015; Pedisic et al., 2013). In addition, patients with chronic NP may suffer from fear of movement (kinesiophobia) (Asiri et al., 2021; Demirbüken et al., 2016; Uluğ et al., 2016), the higher severity of which is associated with greater pain and disability as well as lower quality of life (Luque-Suarez et al., 2019).

Furthermore, previous research shows that NP is associated with reduced cervical range of motion (ROM) (Rudolfsson et al., 2012) as well as alterations in cervical motor control which have been observed in patients with NP through impaired activation of the deep cervical flexor muscles demonstrated during the craniocervical flexion test (CCFT) (Chiu et al., 2005; Jull et al., 2008) and altered cervical sensorimotor function (de Vries et al., 2015; Kristjansson & Treleaven, 2009; Stanton et al., 2016). More specifically, sensorimotor deficits commonly seen in patients with NP can arise from abnormal cervical afferent input (Kristjansson & Treleaven, 2009) affecting patients' ability to sense the position and movement of body parts and, consequently, how they respond to external and internal changes in the environment throughout their daily activities (Proske & Gandevia, 2012). In addition, the results of a recent study suggest that NP as such can also significantly affect cervical sensorimotor control function, as an increased error in cervical joint repositioning was observed in healthy subjects after experimentally induced NP (Wang et al., 2022). Accordingly, altered cervicocephalic kinesthetic awareness (de Vries et al., 2015; Stanton et al., 2016) and postural balance (Ruhe et al., 2011) are commonly identified in patients with NP. Moreover, it has been suggested that altered sensorimotor control due to cervical proprioceptive deficits could contribute to the recurrence and chronicity of NP (Kristjansson & Treleaven, 2009; Qu et al., 2022; Röijezon et al., 2015), while there is growing evidence that adaptations in neuromuscular function (e.g., changes in muscle properties and activity, mobility, sensorimotor control) can occur not only in patients with chronic NP, but also in individuals with recurrent NP during a period in remission (Alalawi et al., 2022; Devecchi et al., 2021). These findings suggest that restoration of neuromuscular function is along with pain relief important in the management of patients with NP disorders and that neuromuscular characteristics should be monitored during clinical assessment using objective outcome measures to properly understand the effectiveness of rehabilitation approaches (Jull, 2016). In this regard, addressing sensorimotor control deficits has been proposed as one of the most important aspects of treating patients with NP (Kristjansson & Treleaven, 2009; Peng et al., 2021; Treleaven, 2008).

To date, the effects of various rehabilitation approaches on chronic NP have been investigated and evaluated. Nevertheless, research shows that patient outcomes remain suboptimal, underscoring the need to develop more effective approaches for treating chronic NP (Bier et al., 2018; Blanpied et al., 2017; Castellini et al., 2022; Sterling et al., 2019). Different types of cervical sensorimotor control exercises that aim to enhance cervical kinesthetic functions (i.e., position sense, movement sense) have shown promising results when used in combination or as stand-alone rehabilitation program for chronic NP, in terms of improving specific outcomes, including pain, neck disability, quality of life, kinesiophobia, neck mobility and motor control, as well as sensorimotor function (Cetin et al., 2022; Espí-López et al., 2021; Gallego Izquierdo et al., 2016; Humphreys & Irgens, 2002; Jull et al., 2007; Nusser et al., 2021; Pérez-Cabezas et al., 2020; Reddy et al., 2021; Revel et al., 1994; Rezaei et al., 2018; Saadat et al., 2019; Sarig Bahat et al., 2015, 2018; Sremakaew et al., 2023; Tejera et al., 2020). To the best of our knowledge, no prior reviews have examined the effectiveness of these training modalities in patients with chronic NP. Previous systematic reviews and meta-analyses have mainly focused on specific training modalities aimed at improving only one aspect of cervical sensorimotor control (Ahern et al., 2020; Grassini, 2022; Gross et al., 2015; McCaskey et al., 2014; Petersen et al., 2013), while others have investigated the effectiveness of motor control exercises (Rasmussen-Barr et al., 2023), which, in contrast to cervical sensorimotor control exercises, are primarily aimed at improving control of craniocervical flexion movement and activation of the deep cervical flexor muscles (de Zoete et al., 2021; Jull et al., 2009). This gap in the literature highlights the necessity of conducting a systematic review and meta-analysis to consolidate evidence on the effects of cervical sensorimotor control training to provide new insights for the treatment of chronic NP.

The aim of this systematic review and meta-analysis was to investigate the effectiveness of cervical sensorimotor control training on the above-described signs and symptoms related to chronic NP disorders. Studies with interventions combining cervical sensorimotor control training with another type of rehabilitation program were excluded from the review in order to investigate causality by isolating the effect of a specific rehabilitation approach.

Methods

The review was conducted according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines (Hutton et al., 2015; Moher et al., 2009) and was registered at the International prospective register of systematic reviews (PROSPERO registration number: CRD42022381714).

Data sources and searches

The electronic databases PubMed, PEDro, ScienceDirect and Web of Science were searched for literature. Gray literature of published interventions and systematic reviews was searched through Google Scholar and DART-Europe E-theses Portal. Reference lists of relevant reviews and their included articles were searched as well as PROSPERO databases to identify any important ongoing and/or unpublished systematic reviews. Unpublished studies were not sought. The databases were systematically searched from inception to November 2023 using the following search string: (neck OR cervical) AND (propriocept* OR kinest* OR kinaest* OR kinemat* OR coordination OR "motor control" OR sensorimotor OR "position sense" OR "movement sense" OR "movement control") AND (training* OR exercise* OR rehabilitation* OR intervention* OR program* OR regime*). As different databases require different search strategies, the search strings for the

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individual databases were adapted. The following filters were used for individual databases: (a) Clinical trial, Randomized controlled trial (PubMed); (b) Clinical trial (PEDro); (c) Research articles (ScienceDirect); (d) Article (Web of Science).

Study selection

Two review authors (I.L. and Z.M.R.) independently screened titles and abstracts. Duplicate records were removed using Microsoft Excel (Microsoft Corporations, Redmond, Washington, USA). The same two review authors evaluated the eligibility of the retrieved full-text articles. Discrepancies that arose during eligibility assessment were resolved through discussion and by consultation with a third author (V.S.) when necessary. Randomized controlled trials (RCTs) and clinical trials were included if they met the following criteria: (1) study population consisted of adults (mean age: 18+ years) with chronic NP (> 3 months duration, traumatic or non-traumatic origin); (2) involving an intervention with cervical sensorimotor control training/exercises that are based on position sense, movement sense and/or movement control during or after active head and neck movements and are aimed to improve cervical sensorimotor control; (3) cervical sensorimotor control training was compared to (a) no treatment or (b) any other conservative or non-conservative treatments. Studies were excluded if cervical sensorimotor control training did not involve active head and neck movements. Studies focusing on other modalities: cervical muscle strengthening and endurance exercises, proprioceptive neuromuscular facilitation, neuromuscular joint facilitation, vestibular rehabilitation, mental imagery exercises, laterality training, and postural balance training were excluded from this review. Interventions where cervical sensorimotor control training was combined with any other type of rehabilitation program were excluded.

Outcome measures

The primary outcomes of interest were objective measures of sensorimotor control function (i.e., cervicocephalic kinesthetic awareness and postural balance) and pain intensity measured by a pain scale (i.e., visual analog scale (VAS) or numerical rating scale (NRS)). The secondary outcomes of the review were subjective functional limitations assessed by neck disability-specific scale (i.e., Neck Disability Index (NDI)), objective measures of cervical ROM and CCFT and subjectively measured quality of life and kinesiophobia.

Data extraction and quality assessment

Two review authors (I.L. and Z.M.R.) extracted the data independently, while the third author (V.S.) checked the accuracy of the entered data. Data on study and patient characteristics, outcome measures and effects on primary and secondary outcomes were extracted. When studies reported more than two intervention groups that could be included in the review, data were extracted from all study arms. When necessary, authors of the included studies were contacted to obtain additional data.

For the included studies, risk of bias was assessed independently by two review authors (I.L. and Z.M.R.) using the PEDro scale (Herbert et al., 1998). The PEDro scale has been shown to be a valid (de Morton, 2009; Macedo et al., 2010) and reliable (Maher et al., 2003) measure for assessing the methodological quality of clinical trials. Trials are considered to be of good to excellent quality if they score at least 6 points (Cashin & McAuley, 2020), which is a widely used cut-off point in the literature (Armijo-Olivo et al., 2015).

The certainty of evidence was assessed according to the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach (Guyatt et al., 2011) and was classified as high, moderate, low, or very low. Certainty of evidence was downgraded according to the: risk of bias, inconsistency, imprecision, indirectness, and publication bias (Furlan et al., 2015).

Data synthesis and analysis

Only studies that provided sufficient data to calculate the standardized mean difference (SMD: Hedges' g) were included in the meta-analysis. The SMD was calculated as the difference between changes from baseline in the intervention and comparator groups based on the reported means, standard deviations (SDs), and sample sizes of each group. If the SD was not available, it was estimated using the standard error (SE), confidence interval (CI), or p-value according to the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2022). In addition, if studies reported the sample size, median and interquartile range, these were used to estimate the mean and SD by using a formula-based method developed by Wan et al. (Wan et al., 2014). In studies with multiple relevant intervention groups, the 'shared' group was split into two or more groups with smaller sample sizes to allow inclusion in the meta-analysis and to examine heterogeneity across intervention arms (Higgins et al., 2022).

A random-effects model was used to pool the results of individual trials. The heterogeneity variance $\tau 2$ was calculated using the restricted maximum likelihood method (Viechtbauer, 2005) and Knapp-Hartung adjustments were used to calculate the CI around the pooled effect (Knapp & Hartung, 2003). Hedges' g values of ≥ 0.2, ≥ 0.5, and > 0.8 were interpreted as small, medium, and large effects, respectively (Ellis, 2010). The between study heterogeneity was assessed using the I2 statistic, where values of 0%-40% might not be important, 30%-60% may represent moderate heterogeneity, 50%-90% may represent substantial heterogeneity, and 75%-100% may represent considerable heterogeneity (Higgins et al., 2022). A subgroup analysis was performed based on the comparator intervention to separately consider the effects of the interventions when compared with no treatment or other conservative or non-conservative treatments. All statistical analyses were performed in R statistical software (version 4.3.0) (R Core Team, 2023) using the "meta" package, and p-values of less than 0.05 were considered statistically significant.

Protocol changes after the initial PROSPERO registration

After the initial PROSPERO registration, but before any analyses were performed, the following changes were made to the protocol and were submitted to our record: slight changes in terminology regarding training modalities; using PEDro scale to assess risk of bias; adding the criterion not to exclude interventions involving ocular exercises; using Hedges' g to calculate effect size and using the data synthesis strategy described in the above paragraph.

Results

Flow of studies through the review

The study selection process is shown in Figure 1. A total of 3860 records were identified through a comprehensive database search strategy, while 2 were found in other sources (i.e.,

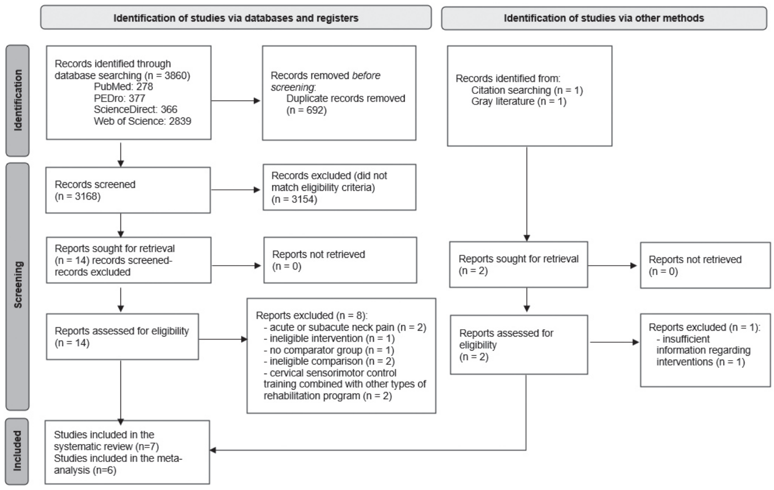

Figure 1. Prisma flowchart illustrating the study selection process

reference and gray literature searches). After removing duplicates and screening articles by title and abstract, 16 papers were retrieved for full-text screening. Altogether, 7 studies (7 papers with 9 intervention comparisons, involving 409 participants) met the inclusion criteria and were included in the systematic review (Gallego Izquierdo et al., 2016; Humphreys & Irgens, 2002; Jull et al., 2007; Revel et al., 1994; Rudolfsson et al., 2014; Sarig Bahat et al., 2018; Tejera et al., 2020). Among them, 6 studies (6 papers with 7 intervention comparisons) that provided sufficient data were included in the meta-analysis (Gallego Izquierdo et al., 2016; Humphreys & Irgens, 2002; Jull et al., 2007; Revel et al., 1994; Sarig Bahat et al., 2018; Tejera et al., 2020). All studies included in the systematic review were RCTs, and two of them were 3-arm studies (Rudolfsson et al., 2014; Sarig Bahat et al., 2018). Two studies appeared to meet the inclusion criteria but were excluded from the review because of ineligible intervention comparisons considering our inclusion criteria (Rezaei et al., 2018; Sarig Bahat et al., 2015).

Characteristics of included trials

A comprehensive overview of all trials (n = 7) that met the predefined criteria is provided in Table 1. The included trials encompassed 9 intervention comparisons that included 8 interventions with cervical sensorimotor control training. A total of 409 participants were included in the trials. Two trials included only women (Jull et al., 2007; Rudolfsson et al., 2014), while in others the proportion of women ranged from 50% to 85% (Gallego Izquierdo et al., 2016; Humphreys & Irgens, 2002; Revel et al., 1994; Sarig Bahat et al., 2018; Tejera et al., 2020). Mean duration of the interventions with cervical sensorimotor control training was 6.1 weeks (4 to 11 weeks). Three interventions included cervical proprioceptive training, consisting of head relocation practice, gaze stability, eye-follow and eye-head coordination exercises (Gallego Izquierdo et al., 2016; Jull et al., 2007; Revel et al., 1994), two interventions included kinematic or neck-specific training using virtual reality (Sarig Bahat et al., 2018; Tejera et al., 2020) and three interventions included eye-head-neck-upper limb coordination exercises (Humphreys & Irgens, 2002), neck coordination exercise with a custom-made training device (Rudolfsson et al., 2014) and kinematic training with a laser pointer (Sarig Bahat et al., 2018), respectively. In four intervention comparisons, the comparator group received no treatment (Humphreys & Irgens, 2002; Revel et al., 1994; Sarig Bahat et al., 2018), while in five intervention comparisons the comparator group received other conservative or non-conservative treatments, including craniocervical flexion training (Gallego Izquierdo et al., 2016; Jull et al., 2007), neck-specific exercises (performing neck movements while maintaining craniocervical flexion) (Tejera et al., 2020), strength training for the neck and shoulders (Rudolfsson et al., 2014), or massage (Rudolfsson et al., 2014).

Regarding the primary outcomes defined in the review, 4 trials investigated the short-term effects on cervicocephalic kinesthetic awareness (cervical position sense or movement sense) (Humphreys & Irgens, 2002; Jull et al., 2007; Revel et al., 1994; Sarig Bahat et al., 2018), 1 on postural balance (Rudolfsson et al., 2014) and 6 on pain intensity (Gallego Izquierdo et al., 2016; Humphreys & Irgens, 2002; Jull et al., 2007; Revel et al., 1994; Sarig Bahat et al., 2018; Tejera et al., 2020), while 1 trial reported the results on the intermediate-term effects on pain intensity (Tejera et al., 2020). Long-term effects on postural balance and pain intensity were only investigated in 1 trial (Rudolfsson et al., 2014). Furthermore, the results on the secondary outcomes defined in the review were reported in 5 trials at short-term follow-up (Gallego Izquierdo et al., 2016; Jull et al., 2007; Revel et al., 1994; Sarig Bahat et al., 2018; Tejera et al., 2020), whereas only one trial included relevant intermediate-term follow-up (Tejera et al., 2020) and another trial included long-term follow-up (Rudolfsson et al., 2014). In the included trials, short-term follow-up was conducted at the end (Gallego Izquierdo et al., 2016; Humphreys & Irgens, 2002; Jull et al., 2007; Rudolfsson et al., 2014; Sarig Bahat et al., 2018; Tejera et al., 2020), 2 weeks (Revel et al., 1994) or 1 month (Tejera et al., 2020) after the intervention, while intermediate- and long-term follow-up was conducted 3 (Tejera et al., 2020) and 6 months (Rudolfsson et al., 2014) after the intervention, respectively.

A quantitative synthesis of the results was performed when adequate data were available for a particular outcome from the included studies. In this regard, only the results on pain intensity and subjective functional limitations at short-term follow-up (considering the earliest follow-up point) were synthesized, while the results on other outcomes could not be summarized quantitatively due to insufficient data and considerable differences in outcome reporting and assessment methods.

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Table 1. Characteristics of included trials (intervention comparisons)

Author and year (study design)	PEDro score	Sample size (I/C)	Age* (I/C) and sex of participants	Intervention duration (weeks)	Modality	Comparator intervention	Intervention dose (minutes/ week)	Outcome measures
Gallego Izquierdo et al., 2016 (RCT)	8	28 (14/14)	I: 29.93(7.34) C: 28.43(6.16) Sex: males (35.7%) and females (64.3%)	8	Cervical proprioceptive training	Craniocervical flexion training	140	CCFT, NDI, PPT, VAS
Humphreys & Irgens, 2002 (RCT)	5	28 (14/14)	22.6 (19-30)† Sex: males (50%) and females (50%)	4	Eye-head-neck-upper limb coordination exercises	No treatment	NR (2 sessions/day)	HRA, VAS
Jull et al., 2007 (RCT)	6	58 (28/30)	I: 39.0(11.6) C: 42.7(10.8) Sex: females	6	Cervical proprioceptive training	Craniocervical flexion training	70-140	JPE, NDI, NRS
Revel et al., 1994 (RCT)	4	60 (30/30)	48(14) (25-80)† I: 47‡ (25-74)† C: 46.5‡ (25-80)† Sex: males (15%) and females (85%)	8	Cervical proprioceptive training	No treatment	60-80	Drug intake (NSAID, AD), HRA, ROM, self-assessed functional improvement, VAS
Rudolfsson et al., 2014 (RCT)	6	70 (35/35)	I: 50.7(8.6) C: 51.6(9.0) Sex: females	11	Neck coordination exercise with a custom-made training device	Strength training for neck and shoulders	60	Postural sway, precision of goal directed arm movements
Rudolfsson et al., 2014 (RCT)	6	66 (35/31)	I: 50.7(8.6) C: 51.2(9.0) Sex: females	11	Neck coordination exercise with a custom-made training device	Massage	60	Fast axial cervical rotations, NRS, postural sway, precision of goal directed arm movements, ROM
Sarig Bahat et al., 2018 (RCT)	7	60 (30/30)	I: 48‡ (35.5, 59)§ C: 48‡ (35, 59)§ Sex: males (26.7%) and females (73.3%)	4	Kinematic training using a laser pointer	No treatment	80	Cervical motion kinematics, EQ-5D, GPE, NDI, ROM, TSK, VAS
Sarig Bahat et al., 2018 (RCT)	7	60 (30/30)	I: 48‡ (38.5, 57.5)§ C: 48‡ (35, 59)§ Sex: males (30.0%) and females (70.0%)	4	Kinematic training using virtual reality	No treatment	80	Cervical motion kinematics, EQ-5D, GPE, NDI, ROM, TSK, VAS
Tejera et al., 2020 (RCT)	7	44 (22/22)	29.7(10.81) I: 32.72(11.63) C: 26.68(9.21) Sex: males (47.7%) and females (52.3%)	4	Virtual reality-based neck-specific training	Neck-specific exercises	NR (2 sessions/ week)	CPM, FABQ, NDI, PASS-20, PCS, PPT, ROM, TS, TSK, VAS

Note. AD: analgesic drugs; C: comparator group; CCFT: Craniocervical flexion test; CPM: Conditioned Pain Modulation; EQ-5D: EuroQoL 5-Dimension Questionnaire; FABQ: The fear-avoidance beliefs questionnaire; GPE: Global perceived effect; HRA: head repositioning accuracy; I: intervention group; JPE: joint position error; NDI: Neck Disability Index (subjective functional limitations related to neck pain disorders); NR: not reported; NRS: numerical rating scale; NSAID: nonsteroidal anti-inflammatory drugs; PASS-20: Pain Anxiety Symptoms Scale; PCS: Pain Catastrophizing Scale; PPT: pressure pain thresholds; RCT: randomized controlled trial; ROM: Active Cervical Range of Motion; TS: Temporal Summation; TSK: Tampa Scale of Kinesiophobia; VAS: visual analog scale (pain intensity). *Values are presented as mean(SD) unless otherwise indicated. † Age range (min-max). ‡ Median age. § Interquartile range of age (Q1, Q1).

Table 2. PEDro scores of included studies

Study	Eligibility criteria	Random allocation	Concealed allocation	Baseline comparability	Blind subjects	Blind therapist	Blind assessors	Adequate follow-up	Intention-to-treat analysis	Between-group comparisons	Point estimates and variability	Total score (0 to 10)
Gallego Izquierdo et al. (2016)	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	8
Humphreys & Irgens (2002)	Y	Y	N	Y	N	N	N	Y	N	Y	Y	5
Jull et al. (2007)	Y	Y	N	Y	N	N	Y	Y	N	Y	Y	6
Revel et al. (1994)	Y	Y	N	Y	N	N	N	N	N	Y	Y	4
Rudolfsson et al. (2014)	Y	Y	N	Y	N	N	Y	Y	N	Y	Y	6
Sarig Bahat et al. (2018)	Y	Y	Y	Y	N	N	Y	N	Y	Y	Y	7
Tejera et al. (2020)	Y	Y	Y	Y	N	N	N	Y	Y	Y	Y	7

Note. N: no; PEDro: Physiotherapy Evidence Database; Y: yes.

Table 3. Summary of certainty of evidence using the GRADE approach

Outcome	Number of participants and studies	Risk of Bias*	Inconsistency†	Imprecision‡	Indirectness§	Publication Bias¶	Certainty of evidence - GRADE
Comparison: Cervical sensorimotor control training vs. no treatment							
Short-term follow-up							
Cervicocephalic kinesthetic awareness	164 participants 3 studies (4 intervention comparisons)	Serious limitations, downgraded by one level.	No serious inconsistency.	Serious limitations, downgraded by one level.	No serious indirectness.	No serious publication bias.	++00 LOW
Pain intensity	164 participants 3 studies (4 intervention comparisons)	Serious limitations, downgraded by one level.	No serious inconsistency.	Serious limitations, downgraded by one level.	No serious indirectness.	No serious publication bias.	++00 LOW
Subjective functional limitations	76 participants 1 study (2 intervention comparisons)	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	No serious indirectness.	No serious publication bias.	+++0 MODERATE
Cervical range of motion	136 participants 2 studies (3 intervention comparisons)	Serious limitations, downgraded by one level.	No serious inconsistency.	Serious limitations, downgraded by one level.	No serious indirectness.	No serious publication bias.	++00 LOW
Quality of life	76 participants 1 study (2 intervention comparisons)	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	No serious indirectness.	No serious publication bias.	+++0 MODERATE
Kinesiophobia	76 participants 1 study (2 intervention comparisons)	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	No serious indirectness.	No serious publication bias.	+++0 MODERATE
Comparison: Cervical sensorimotor control training vs. other conservative or non-conservative treatments							
Short-term follow-up							
Cervicocephalic kinesthetic awareness	58 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Postural balance	86 participants 1 study (2 intervention comparisons)	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Pain intensity	130 participants 3 studies	No serious risk of bias.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	+000 VERY LOW
Subjective functional limitations	130 participants 3 studies	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Cervical range of motion	44 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Craniocervical flexion test	28 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Kinesiophobia	44 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
1-month follow-up							
Pain intensity	44 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW

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Table 3. Summary of certainty of evidence using the GRADE approach

Outcome	Number of participants and studies	Risk of Bias*	Inconsistency†	Imprecision‡	Indirectness§	Publication Bias¶	Certainty of evidence - GRADE
Subjective functional limitations	44 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Cervical range of motion	44 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Kinesiophobia	44 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Intermediate-term follow-up							
Pain intensity	44 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Subjective functional limitations	44 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Cervical range of motion	44 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Kinesiophobia	44 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Long-term follow-up							
Postural balance	84 participants 1 study (2 intervention comparisons)	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Pain intensity	57 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW
Cervical range of motion	57 participants 1 study	No serious risk of bias.	No serious inconsistency.	Serious limitations, downgraded by one level.	Serious limitations, downgraded by one level.	No serious publication bias.	++00 LOW

Note. GRADE: Grading of Recommendations Assessment, Development and Evaluation. ++++ (high): We have a lot of confidence that the true effect is similar to the estimated effect. +++0 (moderate): We believe that the true effect is probably close to the estimated effect. ++00 (low): We believe that the true effect might be markedly different from the estimated effect. +000 (very low): We believe that the true effect is probably markedly different from the estimated effect. *Serious limitations were identified if more than 25% of studies were classified as being of less than good quality with a PEDro score < 6. † Serious limitations were identified in case of statistically significant heterogeneity test, I2 ≥ 50%, or if the direction of the study results was different in the majority (≥75%) of studies. ‡ Serious limitations were identified if sample size was smaller than 400, in case of wide confidence intervals (CIs) when data were presented as standardized mean difference, or if comparisons included only a single study. § Serious limitations were identified if the population, interventions and outcomes in the studies were not representative of those defined in the inclusion criteria of the review. ¶ Serious limitations were identified if the presented study results differed from the original protocol or study objectives.

Risk of bias and certainty of evidence

The results of risk of bias assessment using the PEDro scale are presented in Table 2. PEDro scores ranged from 4 to 8 and the mean PEDro score was 6.1 (SD 1.4). None of the studies met the blind subjects and therapist criteria and most did not meet the concealed allocation and intention-to-treat analysis criteria (Humphreys & Irgens, 2002; Jull et al., 2007; Revel et al., 1994; Rudolfsson et al., 2014).

The summary of certainty of evidence using the GRADE approach is presented in Table 3 and shows that the certainty of evidence (GRADE) for individual outcomes ranged from very low to moderate.

Effect of cervical sensorimotor control training versus no treatment

The results of three trials involving four interventions (n = 164; low certainty of evidence due to high risk of bias and imprecision) showed significant effectiveness of cervical sensorimotor control training for improving cervicocephalic

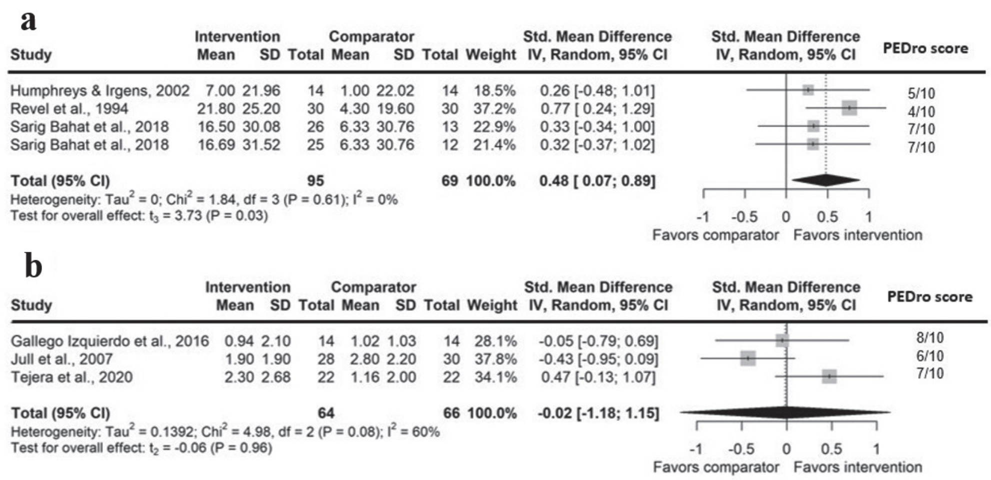

Figure 2. Forest plots for the effect of cervical sensorimotor control training versus (a) no treatment (3 trials, n = 164) (Humphreys & Irgens, 2002; Revel et al., 1994; Sarig Bahat et al., 2018) or (b) other conservative or non-conservative treatments (3 trials, n = 130) (Gallego Izquierdo et al., 2016; Jull et al., 2007; Tejera et al., 2020) on pain intensity at short-term follow-up

kinesthetic awareness at short-term follow-up compared with no treatment (Humphreys & Irgens, 2002; Revel et al., 1994; Sarig Bahat et al., 2018), which was associated with greater improvement in head repositioning accuracy, measured with a laser pointer ($p<0.05$) (Humphreys & Irgens, 2002; Revel et al., 1994), and various cervical motion kinematics measured with a customized neck virtual reality system ($p<0.05$) (Sarig Bahat et al., 2018). In addition, the above-mentioned three trials with four interventions also compared the short-term effects of cervical sensorimotor control training and no treatment on pain intensity (Humphreys & Irgens, 2002; Revel et al., 1994; Sarig Bahat et al., 2018). The pooled SMD was 0.48 (95% CI: 0.07 to 0.89; p = 0.03; n = 164; I2 = 0%; low certainty of evidence due to high risk of bias and imprecision) (Figure 2a), indicating a medium effect in favor of cervical sensorimotor control training on reducing pain intensity at short-term follow-up compared to no treatment.

With respect to the secondary outcomes, based on pooled results from a single 3-arm trial involving 76 subjects, there is moderate certainty of evidence (due to imprecision) for no additional benefit of cervical sensorimotor control training compared with no treatment in reducing subjective functional limitations at short-term follow-up (SMD = 0.32; 95% CI: -0.90 to 1.53; p = 0.19; I2 = 0%) (Figure 3a) (Sarig Bahat et al., 2018). Furthermore, the short-term effects of cervical sensorimotor control training on improving cervical ROM were compared with no treatment in two trials (n = 136; low certainty of evidence due to high risk of bias and imprecision) (Revel et al., 1994; Sarig Bahat et al., 2018). In the first trial, the intervention group demonstrated greater improvement in cervical ROM (measured with a linear measure) from right to left rotation (p = 0.007), but not from flexion to extension (Revel et al., 1994), while in the second trial (3-arm trial), no differences were found between groups in cervical ROM improvement (measured with a customized neck virtual reality system) (Sarig Bahat et al., 2018). According to the results of the aforementioned 3-arm trial, there is moderate certainty of evidence (n = 76; limitations in imprecision) that there is no difference in the short-term effects of cervical sensorimotor control training on quality of life (assessed by EuroQoL 5-Dimension Questionnaire) and kinesiophobia (assessed by Tampa Scale of Kinesiophobia (TSK)) compared to no treatment (Sarig Bahat et al., 2018).

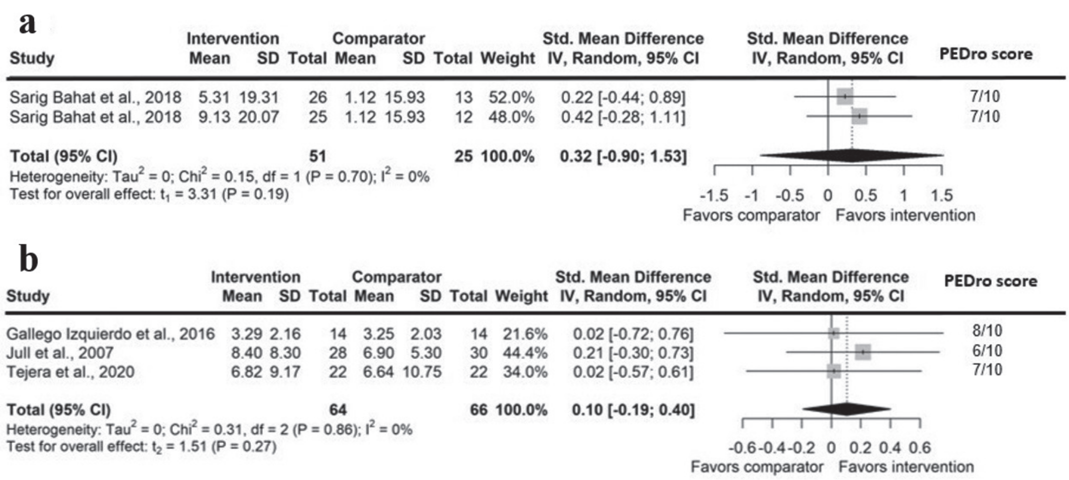

Figure 3. Forest plots for the effect of cervical sensorimotor control training versus (a) no treatment (1 3-arm trial, n = 76) (Sarig Bahat et al., 2018) or (b) other conservative or non-conservative treatments (3 trials, n = 130) (Gallego Izquierdo et al., 2016; Jull et al., 2007; Tejera et al., 2020) on subjective functional limitations at short-term follow-up

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Effect of cervical sensorimotor control training versus other conservative or non-conservative treatments

Regarding the primary outcomes, a single trial (n = 58; low certainty of evidence due to imprecision and indirectness) comparing the short-term effects of cervical sensorimotor control training and craniocervical flexion training on cervicocephalic kinesthetic awareness (by measuring cervical joint position error (JPE) with a 3-Space Fastrak device) reported greater improvement in the former group, which was related to greater reduction in JPE from right rotation (p<0.05), but there were no differences in reduction in JPE from left rotation and extension between the two groups (Jull et al., 2007). Furthermore, a 3-arm trial reported no differences in the short- and long-term effects of cervical sensorimotor control training on improving postural balance (measured with a force platform) compared with strength training for the neck and shoulders or massage (short-term follow-up: n = 86, long-term follow-up: n = 84; low certainty of evidence due to imprecision and indirectness) (Rudolfsson et al., 2014). Three trials involving 130 subjects examined the short-term effects of cervical sensorimotor control training on pain intensity in comparison with other conservative or non-conservative treatments (Gallego Izquierdo et al., 2016; Jull et al., 2007; Tejera et al., 2020). At short-term follow-up, cervical sensorimotor control training was no better than other conservative or non-conservative treatments in reducing pain (SMD = -0.02; 95% CI: -1.18 to 1.15; p = 0.96; I2 = 60%; very low certainty of evidence due to inconsistency, imprecision and indirectness) (Figure 2b). Furthermore, no between-group differences were reported in reduction of pain intensity at 1-month and intermediate-term follow-up (1 trial; n = 44; low certainty due to imprecision and indirectness) (Tejera et al., 2020), as well as in reduction of pain intensity at long-term follow-up (1 trial; n = 57; low certainty due to imprecision and indirectness) (Rudolfsson et al., 2014).

The short-term effects of cervical sensorimotor control training on subjective functional limitations compared with other conservative or non-conservative treatments were examined in three trials involving 130 subjects (Gallego Izquierdo et al., 2016; Jull et al., 2007; Tejera et al., 2020). As shown in Figure 3b, the overall effect was non-significant, indicating that cervical sensorimotor control training was no better than other conservative or non-conservative treatments in reducing subjective functional limitations in the short term (SMD = 0.10; 95% CI: -0.19 to 0.40; p = 0.27; I2 = 0%; low certainty of evidence due to imprecision and indirectness). Furthermore, a single trial (n = 44; low certainty due to imprecision and indirectness) reported significant between-group differences (p<0.05) in reduction of kinesiophobia (assessed by TSK) at intermediate-term follow-up in favor of cervical sensorimotor control training when compared with neck-specific exercises (Tejera et al., 2020). However, the aforementioned trial also found no differences between groups in the effects on subjective functional limitations at 1-month and intermediate-term follow-up, on cervical ROM (measured with the cervical range of motion (CROM) device) at short-term, 1-month and intermediate-term follow-up, and on kinesiophobia at short-term and 1-month follow-up (Tejera et al., 2020). In addition, cervical sensorimotor control training was found to be no better than craniocervical flexion training in improving performance in CCFT at short-term follow-up, based on low certainty of evidence (1 trial; n = 28; limitations in imprecision and indirectness) (Gallego Izquierdo et al., 2016), nor in improving cervical ROM at long-term follow-up when compared with massage, as reported in a 3-arm trial (n = 57; low certainty of evidence due to imprecision and indirectness) (Rudolfsson et al., 2014).

Discussion

This systematic review and meta-analysis aimed to investigate the effectiveness of cervical sensorimotor control training for the management of chronic NP disorders by evaluating its effects on various subjective and objective outcome measures. The review found low-certainty evidence that cervical sensorimotor control training was superior to no treatment for improving cervicocephalic kinesthetic awareness and reducing pain intensity at short-term follow-up. However, the only study that showed a significant effect on pain and significantly influenced the pooled effect showed high risk of bias (Revel et al., 1994), which may lead to an overestimation of the actual intervention effect. Furthermore, according to low-to-moderate certainty of evidence, there were no between-group differences at short-term follow-up in improving subjective functional limitations, ROM, quality of life and kinesiophobia. When cervical sensorimotor control training was compared to other conservative or non-conservative treatments, no differences were found between groups in improving pain and ROM at any follow-up (very low-to-low certainty of evidence), subjective functional limitations at short-term, 1-month and intermediate-term follow-up (low-certainty evidence), performance on the CCFT at short-term follow-up (low-certainty evidence), postural balance at short- and long-term follow-up (low-certainty evidence), and kinesiophobia at short-term and 1-month follow-up (low-certainty evidence). There is low-certainty evidence that cervical sensorimotor control training was better than other conservative or non-conservative treatments for reducing kinesiophobia at intermediate-term follow-up, as well as cervicocephalic kinesthetic awareness at short-term follow-up, however this was demonstrated only for one out of three head-to-neutral movement directions.

While the presented results are based on a smaller number of studies, our review fills an important gap in the literature by providing a comprehensive overview of the available evidence concerning the effectiveness of cervical sensorimotor control training for chronic NP disorders by examining the effects on several objective and subjective outcomes. In contrast, previous systematic reviews and meta-analyses have predominantly focused on specific training modalities aimed at improving only one aspect of cervical sensorimotor control (i.e., eye-head coordination exercises, head relocation practice and/or gaze stability or eye-follow exercises (Gross et al., 2015; McCaskey et al., 2014; Petersen et al., 2013), and neck-specific training using virtual reality (Ahern et al., 2020; Grassini, 2022)). As a consequence, the focus of these reviews was limited and included a narrower range of interventions. The findings of the present review question the effectiveness of cervical sensorimotor control training as a stand-alone rehabilitation program for chronic NP disorders, particularly when compared with other conservative or non-conservative treatments. However, such training might demonstrate greater effects as part of a multimodal treatment, as many recent studies have shown positive results from interventions combining cervical sensorimotor control training with other types of rehabilitation approaches (Cetin et al., 2022; Espí-López et al., 2021; Nusser et al., 2021; Pérez-Cabezas et al., 2020; Reddy et al., 2021; Saadat et al., 2019; Sremakaew et al., 2023).

Cervical sensorimotor control exercises are thought to improve position and movement sense of the cervical spine and improve neural connections between the neck, eyes and vestibular system (Bolton, 1998; Gallego Izquierdo et al., 2016; Jull et al., 2007; Qu et al., 2022; Sarig Bahat et al., 2015). The reduction in perceived neck pain when training precise head and neck movements with these exercises could be due to improved fine control of head and neck movements in response to surrounding stimuli (Gallego Izquierdo et al., 2016; Nusser et al., 2021; Qu et al., 2022; Sarig Bahat et al., 2015, 2018), which may lead to better pain control (Revel et al., 1994). This notion has been supported by a recent article in which experimentally induced neck pain in healthy subjects resulted in increased cervical JPE when moving from flexion to the neutral position (Wang et al., 2022). These results demonstrate that the presence of pain is associated with altered cervicocephalic kinesthetic awareness, implying that an improvement in the latter could conversely have an influence on neck pain. In addition to the improved ability to move the head further and more precisely (Sarig Bahat et al., 2015, 2018), specific exercises for sensorimotor control of the cervical spine (i.e., cervical proprioceptive training) have also shown effects on other aspects of neuromuscular function, specifically the coordination between the deep and superficial cervical flexors, as measured by performing CCFT (Gallego Izquierdo et al., 2016), which could lead to a reduction in neck pain due to more efficient muscle recruitment patterns and support of the cervical segments (Jull et al., 2007; Mayoux-Benhamou et al., 1994). Moreover, eye-head coordination exercises could have an effect on the activation of the suboccipital muscles (Bexander & Hodges, 2023), which, like the deep cervical flexors, have a high density of muscle spindles (Boyd-Clark et al., 2002; Liu et al., 2003), further indicating the effect of such training on neuromuscular coordination of the deep cervical muscles.

Although the results of this review showed that cervical sensorimotor control training was not superior in terms of its effects on most outcomes, significant improvements in cervicocephalic kinesthetic awareness were demonstrated. Moreover, the same three studies with four intervention comparisons that reported significant effects of cervical sensorimotor control training for improving cervicocephalic kinesthetic awareness in the short term compared with no treatment also demonstrated a significant overall effect on pain reduction at short-term follow-up in favor of cervical sensorimotor training in the meta-analysis (Humphreys & Irgens, 2002; Revel et al., 1994; Sarig Bahat et al., 2018). In view of the above, exercises aimed at enhancing cervical sensorimotor control could be considered an important element in the rehabilitation of patients with chronic NP disorders. Nevertheless, as findings of this review are based on a small number of studies, it is not possible to draw conclusions about the effectiveness of cervical sensorimotor control training for the management of chronic NP disorders based on the currently available evidence. Therefore, further studies of high quality are needed in this research area, that would focus not only on the assessment of subjective but also on objective outcome measures (e.g., neck mobility and motor control), which are equally important for clinical evaluation.

Limitations

The findings of our review are based on very low-to-moderate certainty of evidence and should be considered with caution. Given the small number of included studies and the associated small sample sizes, imprecision was the most common reason for downgrading the certainty of evidence. Indirectness was also a common limitation due to nonrepresentative populations in certain studies that included only one sex (i.e., women) (Jull et al., 2007; Rudolfsson et al., 2014) or included only participants with chronic non-specific NP thereby excluding chronic NP of traumatic origin (Gallego Izquierdo et al., 2016; Rudolfsson et al., 2014; Tejera et al., 2020). In addition, 2 of the 7 included studies presented with high risk of bias, which further limited the evidence regarding the effects on specific outcomes (Humphreys & Irgens, 2002; Revel et al., 1994). Furthermore, the pooled results were presented with wide 95% CIs, which is related to the small number of studies and, in one case, to substantial heterogeneity between studies. The latter may be due to variability in the outcome measures, as 1 study used NRS (Jull et al., 2007), while the other 2 studies used VAS to measure pain intensity (Gallego Izquierdo et al., 2016; Tejera et al., 2020). Lastly, due to the lack of available data, variability in the outcome measurements and lack of longer-term follow-ups we were unable to synthesize the evidence regarding the effects on the objective and certain subjective outcomes, which, in addition to pain and subjective functional limitations, are also important health-related outcomes in clinical practice.

Conclusions

There is low-certainty evidence that cervical sensorimotor control training is more effective for improving cervicocephalic kinesthetic awareness and reducing pain in the short term compared to no treatment, and for reducing kinesiophobia in the intermediate term compared to other conservative or non-conservative treatments. However, based on the available evidence, no conclusions can be drawn about the effectiveness of cervical sensorimotor control training for the management of chronic NP disorders as a stand-alone rehabilitation program. Although the aim of our systematic review and meta-analysis was to investigate solely the effectiveness of cervical sensorimotor control training to investigate the causality by isolating the effect of a specific rehabilitation approach, clinical practice guidelines support multimodal treatment approaches. Therefore, more concise evidence should be gathered in the future to investigate the effectiveness of combined treatment approaches including also cervical sensorimotor control exercises.

Conflict of interest

The authors declare no conflict of interest.

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Data availability

Data (i.e., material used for the review, including detailed database search process, data extraction, data used for analyses, code and documentation of statistical analysis, etc.) are available from the corresponding author upon reasonable request.

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ORIGINAL SCIENTIFIC PAPER

Exploring Anthropometric Correlates of Performance Across Playing Positions in Youth Male Water Polo

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Abstract

This study aimed to identify position-specific anthropometric differences in anthropometric status and to evaluate anthropometric predictors of performance level in youth male water polo players. The participants were youth male water polo players (n = 104, age: 17-19 years) from Croatia and Montenegro. In addition to playing position (goalkeeper, outer player, inner player/center) and performance level (high-level group vs. top-level group/members of National team), 21 anthropometric variables were included. Analysis of variance and discriminant canonical analyses were performed to define differences among playing positions in terms of anthropometric status. Logistic regressions with performance-level as a criterion (outcome) was performed to identify associations between anthropometric variables and outcome for each playing position. Centers who were taller (OR = 1.23, 95% CI: 1.04--1.45), had lower subscapular skinfold (OR = 0.84, 95% CI: 0.67--0.98), and had larger chest circumferences were more likely to be grouped in top-level group (OR = 1.15, 95% CI: 1.03--1.31). The greater likelihood for being grouped into top-level group was evidenced for those outer players who were taller (OR = 1.20, 95% CI: 1.04--1.41), had longer arms (OR = 1.21, 95% CI: 1.01--1.44), and had lower values of chest skinfold (OR = 0.57, 95% CI: 0.32--0.83), triceps skinfold (OR = 0.80, 95% CI: 0.66--0.98), and subscapular skinfold (OR = 0.75, 95% CI: 0.47--0.89). Anthropometric variables were not significantly associated with performance level in goalkeepers. Talent, skill, and tactical awareness remains essential for all water polo players, but identified anthropometric attributes should be considered when selecting players for successful performance at each playing position.

Keywords: *anthropometry, adolescent, athletic performance, anatomical locations*

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Introduction

Owing to the necessity of constant swimming and the fact that physical contact between players is permitted, water polo is considered a highly physically demanding sport (Kontic et al., 2017; Perazzetti et al., 2023; Uljevic et al., 2013). Water polo players cover significant distances during matches, with position-specific demands, and the game requires a combination of aerobic and anaerobic fitness, with blood lactate levels >8 mmol/L indicating high-intensity efforts (Melchiorri et al., 2010). Specific anthropometric characteristics, physiological parameters, and throwing velocity are important factors in player performance, whereas heart rate monitoring during matches reveals the importance of aerobic capacity (Chirico et al., 2021; Galy et al., 2014).

In water polo, the interplay between "outer" and "inner" players is crucial for a team's success. Each of these roles demands a unique set of skills and physical attributes. The outer players (drivers/wings) need to be quick and agile to drive toward the goal, create passing lanes, and defend against counterattacks. On the other hand, inner players (Center Forward/Center Back) engage in intense physical wrestling near the goal, requiring strength to hold their position and power to shoot or defend. Finally, the goalkeeper in water has a unique combination of physical and mental attributes, with taller goalkeepers having an advantage in covering the goal and blocking the shots. As a result of specific game duties, a specific anthropometric structure and body structure are essential for successful game performance (Dimitric et al., 2022; Ferragut et al., 2011)

Research on male water polo players' anthropometric characteristics and body composition reveals distinct profiles across playing positions (Fritz et al., 2022; Kovačević et al., 2023). In general, centers are massive and tall players, and body length (including body height and arm span) is an important characteristic of goalkeepers (Fritz et al., 2022). In regard to the association with performance level, larger palm size and chest girth were associated with higher performance level when low-level and high-level teams were compared, indicating the importance of specific anthropometric indices in the selection of successful players (Pooya et al., 2016). However, when high-level teams were compared in terms of their anthropometrics, no significant differences were detected (Gardasevic et al., 2021; Vasiljevic et al., 2021).

The aims of this study were (i) to identify position-specific anthropometric differences in anthropometric status and (ii) to evaluate anthropometric predictors of performance level in youth male water polo players. Initially, we hypothesized that (i) the studied anthropometric variables would significantly distinguish playing positions (outer players, inner players, and goalkeepers) and that (ii) significant correlations between the anthropometric variables and performance level would be established for each of the three playing positions.

Methods

Participants

The participants in this study were 104 youth water polo players from Croatia and Montenegro. At the time of the experiment, they were all 17–19 years old. All players had been engaged in water polo training and competition for more than 8 years and were members of Croatian and Montenegrin clubs, including the national champions of both countries for the observed season. All players were members of teams who competed in national championships but also in regional water polo leagues, which is known as one of the best team-level competitions in the world. Within the sample, we included all members of the youth national teams of Croatia and Montenegro (altogether 39 players).

The study was approved by the Ethical Board of the Faculty of Kinesiology, University of Split. Players were initially invited to participate via the national Water Polo Federations of Croatia and Montenegro. Participants above the age of 18 years provided informed consent, whereas for those younger than 18 years, parental consent was provided.

Variables and measurement

In this study, the variables were primary playing position, performance level, and anthropometric indices. The playing position was reported by players' coaches and included the left wing, left driver (flat), right wing, right driver (flat), center (hole set), point, and goalkeeper. For the purpose of this study, playing positions were later grouped into goalkeepers, outer players (wings, drivers), and inner players—centers/hole sets and points. The performance level was checked with the national water polo federations of Croatia and Montenegro, and all players who were on the list for the national team over the last three years were grouped into the top-level group (national team members), whereas the others were clustered into the high-level group (club members).

Anthropometric characteristics included the following variables: body height (cm), body mass (kg), palm diameter/palm size (cm), arm length (cm), arm span (cm), leg length (cm), foot length (cm), chest skinfold (mm), triceps skinfold (mm), subscapular skinfold (mm), abdominal skinfold (mm), thigh skinfold (mm), arm circumference (cm), calf circumference (cm), thigh circumference (cm), chest circumference (cm), abdominal (waist) circumference (cm), elbow breadth (cm), wrist breadth (cm), knee breadth (cm), and ankle breadth (cm). Anthropometric variables were measured with Seca stadiometers and scales (Seca, Birmingham, UK), a skinfold caliper (Holtain, London, UK), and measuring tapes and anthropometers (Martin France). All the measurements were taken by experienced and licensed evaluators and were performed according to the standards for anthropometry assessment (Norton & Eston, 2018).

Statistics

All variables were checked for normality of distributions via the Kolmogorov‒Smirnov test, and descriptive statistics included calculations of means and standard deviations. Differences among playing positions were checked by analysis of variance (ANOVA), with consecutive post hoc tests when appropriate. Multivariate analysis of differences in anthropometric status among playing positions comprised of calculation of the canonical discriminant analysis.

The association between anthropometric indices and performance level was defined by performing logistic regression for binarized criteria (high-level players, coded as "1" vs. top-level players, coded as "2"). Odds ratios (ORs) with corresponding 95% confidence intervals (95% CIs) are reported.

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Logistic regressions were calculated separately for goalkeepers, outer players, and inner players (centers).

Statistica ver 13.5 (Tibco Inc. Palo Alto, CA, USA) was used for all calculations, and a p-level of 95% was applied.

Results

Descriptive statistics and univariate differences among playing positions in terms of anthropometric variables are presented in Table 1. Playing positions significantly differed in almost all the anthropometric variables. Significant ANOVA differences were found for body height, mass, lengths of body segments, all skinfold measures, all circumferences, and three of the four breadths. Post hoc analysis revealed significant differences between the outer players and the remaining two positions in length, body height, and girth measures, with goalkeepers and centers being taller, having longer body segments, and having thicker bone segments than the outer players. Compared with goalkeepers and outer players, center players had significantly greater values of skinfold measures and circumferences.

Table 1. Descriptive statistics for anthropometric variables with univariate differences among playing position (ANOVA – analysis of variance)

	Inner players (Centers) n = 35	Goalkeepers n = 19	Outer players n = 50	ANOVA
	Mean±SD	Mean±SD	Mean±SD	F test (p)
Body height (cm)	189.83±5.81 #	189.68±6.78 #	183.83±4.96	14.61 (0.001)
Body mass (kg)	91.51±8.79 #, $	82.04±8.38	80.14±7.2	21.85 (0.001)
Palm diameter (cm)	24.7±1.37	24.04±0.97	23.68±1.12	7.64 (0.001)
Arm length (cm)	82.64±5.8 #	83.14±4.2 #	79.2±3.9	7.82 (0.001)
Arm span (cm)	197.96±7.07 #	198.98±7.26 #	191.4±6.47	13.49 (0.001)
Leg length (cm)	100.19±6.89 #	101.65±4.89 #	97.48±5.99	3.94 (0.02)
Foot length (cm)	28.65±1.15 #	28.21±1.06 #	27.37±1.28	12.23 (0.001)
Chest skinfold (mm)	10.29±3.2 #, $	8.65±2.46 #	9.21±2.43	2.7 (0.07)
Triceps skinfold (mm)	12.37±6.24	9.93±2.56	11.65±3.34	1.88 (0.16)
Subscapular skinfold (mm)	14.19±3.64 #, $	10.89±2.76 #	12.07±2.93	7.89 (0.001)
Abdominal skinfold (mm)	16.52±5.78 #, $	10.94±3.61 #	13.49±4.97	8.08 (0.001)
Thigh skinfold (mm)	10.24±2.27 $	8.54±1.32 #	10.01±2.18	4.53 (0.01)
Arm circumference (cm)	33.49±2.38 #, $	30.59±2.21	31.64±1.81	13.9 (0.001)
Calf circumference (cm)	39.46±2.18 $	36.35±4.48 #	38.07±2.88	6.58 (0.001)
Thigh circumference (cm)	59.06±3.63 #, $	55.5±3.11	56.14±3.57	9.25 (0.001)
Chest circumference (cm)	106.15±4.83 #, $	99.2±5.69	101.7±4.71	14.33 (0.001)
Waist circumference (cm)	90.55±5.79 #, $	83.46±5.35	84.38±5.45	15.74 (0.001)
Elbow breadth (cm)	7.68±0.68 #	7.61±0.63	7.35±0.39	4.27 (0.02)
Wrist breadth (cm)	5.93±0.27 #	5.97±0.34 #	5.76±0.31	4.97 (0.01)
Knee breadth (cm)	10.18±0.48 #	10.33±0.45 #	9.95±0.51	4.84 (0.01)
Ankle breadth (cm)	7.48±0.54	7.62±0.45	7.45±0.55	0.66 (0.52)

Legend: # denotes significant post hoc differences compared with outer players, $ denotes significant post hoc differences compared with goalkeepers

The multivariate differences in anthropometric status obtained via discriminant canonical analysis are presented in Table 2. Discriminant analysis revealed two significant functions (discriminant roots). In general, the first function explained the differences between the centers and the remaining two playing positions (goalkeepers and outer players), whereas the second function revealed differences between goalkeepers and outer players in the study variables. Accordingly, body mass, chest circumference, and thigh circumference, together with certain skinfold measures, explained the differences between centers and the remaining two playing positions. When these differences are interpreted in general, center players are characterized by an endomorphic body built, which is clearly the overall morphological/anthropometric structure that distinguishes them from other players. The second function is characterized by negative projections of length measures and body height and positive projections of circumference measures. According to the positioning of the group centroids (positive projection of the centroid of the outer players and negative projection of the centroid of the goalkeepers), when these playing positions are compared, the goalkeepers are taller and have longer limbs (more ectomorphic), whereas the outer players are more muscular (mesomorphic).

The associations between the anthropometric variables and performance level for center players are presented in Figure 1, with several anthropometric indices being significantly associated with outcome. Specifically, those centers who were taller (OR = 1.23, 95% CI: 1.04--1.45), who had lower subscapular skinfold values (OR = 0.84, 95% CI: 0.67--0.98), and had larger chest circumferences (OR = 1.15, 95% CI: 1.03--1.31) were more likely to be grouped into top-level performance group.

Table 2. Multivariate differences in anthropometric status among playing positions calculated via discriminant canonical analysis

	Root 1	Root 2
Body height	0.43	-0.49
Body mass	0.75	-0.12
Palm diameter	0.43	-0.14
Arm length	0.27	-0.39
Arm span	0.36	-0.52
Leg length	0.14	-0.32
Foot length	0.48	-0.33
Chest skinfold	0.25	0.09
Triceps skinfold	0.15	0.18
Subscapular skinfold	0.43	0.17
Abdominal skinfold	0.41	0.23
Thigh skinfold	0.17	0.33
Arm circumference	0.57	0.23
Calf circumference	0.34	0.26
Thigh circumference	0.49	0.08
Chest circumference	0.57	0.23
Waist circumference	0.64	0.07
Elbow breadth	0.26	-0.23
Wrist breadth	0.21	-0.32
Knee breadth	0.14	-0.36
Ankle breadth	-0.02	-0.14
Centroid: Centers	1.20	-0.01
Centroid: Goalkeepers	-0.62	-1.56
Centroid: Outer players	-0.61	0.60
Canonical R	0.66	0.62
Wilks Lambda	0.34	0.61
p-level	0.00	0.00

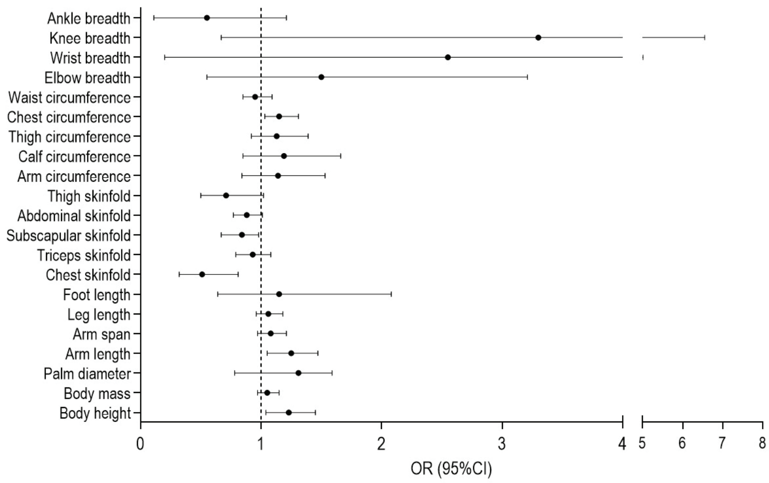

Figure 1. Anthropometric correlates of the performance level for inner players/centers - the results of the logistic regression for binarized criterion (high-level vs. top-level center players)

The correlations between the anthropometric variables and performance level for goalkeepers are presented in Figure 2. Notably, none of the observed anthropometric variables were significantly associated with performance level for goalkeepers.

When logistic regression was calculated for outer players, the greater likelihood for being grouped into top-level group was evidenced for those players who were taller (OR = 1.20, 95% CI: 1.04--1.41), had longer arms (OR = 1.21, 95% CI: 1.01--1.44), and had lower values of chest-skinfold (OR = 0.57, 95% CI: 0.32--0.83), triceps-skinfold (OR = 0.80, 95% CI: 0.66--0.98), and subscapular-skinfold (OR = 0.75, 95% CI: 0.47--0.89) (Figure 3).

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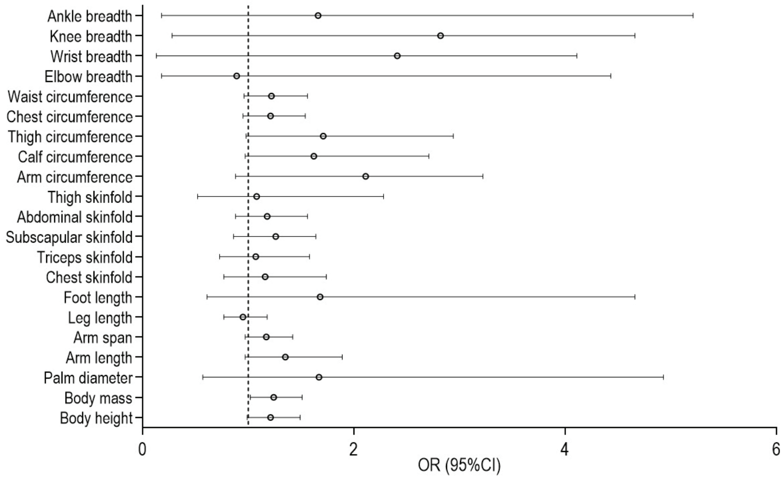

Figure 2. Anthropometric correlates of the performance level for goalkeepers - the results of the logistic regression for binarized criterion (high-level vs. top-level goalkeepers)

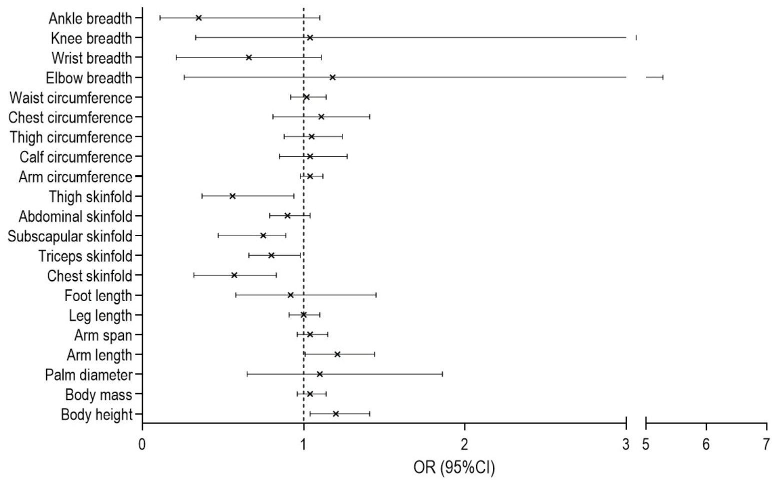

Figure 3. Anthropometric correlates of the performance level for outer players - the results of the logistic regression for binarized criterion (high-level vs. top-level outer players)

Discussion

There are several important findings with respect to the study aims. First, anthropometric status strongly discriminates playing positions in youth water polo. Second, anthropometric indices are correlated with quality level for the backs and out players but not for the goalkeepers. Therefore, our first study hypothesis can be fully accepted, whereas the second study hypothesis could be partially accepted.

Anthropometric indices and playing positions

Our results highlighted distinctive anthropometric structures of three playing positions in youth male water polo players. Among other characteristics, inner players (backs) and goalkeepers are taller and have longer body segments (i.e., leg length and arm length). Further, centers have stronger bones (observed by the diameters of the bone segments) when compared to outer players. Additionally, centers have greater skinfolds (more body fat) and larger circumferences (girths) of specific anatomical locations than do outer players and goalkeepers. These results agree with previous studies performed with Croatian juniors and data obtained from senior-level players (Kondric et al., 2012; Lozovina et al., 2009; Uljevic et al., 2014). In general, such anthropometric structures are connected to players' game duties and are discussed accordingly.

With respect to the anthropometric specifics of goalkeepers, longer body segments are beneficial for several reasons, including (i) increased reach, (ii) enhanced blocking, (iii) improved deflection, (iv) dominating presence, and (v) aerial advantage. Specifically, (i) longer arms and legs translate to a wider reach, allowing goalkeepers to cover a larger portion of the goal. This makes it harder for shooters to find open spaces and increases the likelihood of blocking shots. Additionally, (ii) with greater reach, goalkeepers can effectively increase their blocking area without needing to move as much. This is crucial in water polo, where quick reactions and explosive movements are essential (Martínez et al., 2015).

Importantly, (iii) even if a shot is not blocked completely, longer limbs increase goalkeepers' chances of deflecting the ball, altering its trajectory and potentially preventing a goal. Apart from these clear and understandable performance-specifics, some psychological factors are also important. Specifically, (iv) a goalkeeper with long limbs creates a more imposing presence in the goal, which can intimidate shooters and make them hesitate or rush their shots, and this psychological advantage can be just as important as the physical benefits. Finally, (v) in situations where the ball is lobbed toward the goal, a goalkeeper with long arms can extend higher to catch or punch the ball away, giving them an advantage in aerial duels (Platanou & Thanopoulos, 2002).

The contribution of longer limbs and overall body height in centers is also related to their game duties (Kondric et al., 2012; Uljevic et al., 2014). However, in explaining this, it is important to differentiate offensive and defensive game duties. Considering offensive advantages, the contribution of longer limbs to leverage and reach is likely crucial since longer limbs provide greater leverage when shooting, and such an anthropometric structure allows for more powerful shots. Players with longer limbs can extend further to catch passes and shoot even when tightly guarded, and because of the the contact nature of the water polo this is highly important. Longer legs enable the center forward to rise higher out of the water when shooting, giving them a better angle to shoot over the goalkeeper's head. Longer arms help in controlling the ball in close quarters, making it harder for defenders to steal or block. In general, longer limbs provide an advantage in the physical battles for positions that occur near the goal, which is highly specific for inner players. In other words, inner players can use their reach to hold off defenders or create space for themselves (Idrizović et al., 2013).

The defensive duties of inner players are specific and naturally connected to their anthropometric structure (Kondric et al., 2012). For example, longer arms are crucial for blocking shots from the opposing centers, whereas players in defense who have longer arms can also more efficiently deflect passes intended for the center forward, disrupting the offense. Furthermore, longer limbs allow the inner players (specifically, center back) to cover a larger area around the goal, making it harder for the offense to find open passing lanes or shooting opportunities. With their height and reach, center backs can effectively challenge shots even when they are not directly in front of the shooter, whereas their long reach gives them an advantage in stealing the ball from the opposing center forward or intercepting passes (Idrizović et al., 2013).

Our results on differences among playing positions, with centers having relatively larger bone diameters, are relatively novel. To explain these results, we should first highlight the link between bone diameter and some conditioning capacity. Specifically, it is well documented that larger bone diameters generally correlate with greater skeletal muscle mass and strength (Torres-Costoso et al., 2020). In water polo, this is crucial, especially for centers that engage in intense physical battles and need to generate power for shooting and wrestling. As said, longer and thicker limbs provide better leverage, which is essential for both shooting and defending. This translates to more powerful shots and a greater ability to hold off opponents.

A larger (i.e., more massive) bone structure can contribute to increased stability in the water, making it harder for opposing players to push them off balance. Finally, we must mention one possible link that is not directly related to specific game performance but is also highly important. Specifically, since water polo is a high-impact contact sport, stronger bones with greater density can help reduce the risk of fractures and other injuries (Hart et al., 2020). This is particularly important for center players simply because those players are often in contact with and wrestle from the opponent and are therefore at greater risk of being injured.

Skinfold measures are frequently used as indicators of the overall body fat content, especially in athletes (Ljubojevic et al., 2020; Sermaxhaj et al., 2021). Studies have shown that anthropometric indices are important correlates of athletes' performance levels and are also associated with positions specific to various team sports, including water polo (Gardasevic et al., 2020). With respect to water polo, our findings on higher skinfold measures (i.e., more body fat) in center players are not novel and have already been reported in males and females and for different age categories (Fritz et al., 2022; Nikšić et al., 2020). However, to the best of our knowledge, studies rarely specifically underscore the background of these findings. The context of these results can be explained from three perspectives, emphasizing conditioning, energetic, and biomechanical specificities.

It has already been reported that center players' performance is heavily oriented toward strength and power. These conditioning capacities allow them not only to hold their position effectively but also to wrest for the ball and execute powerful shots. For such purposes, lean muscle mass is essential. However, a certain amount of body fat can contribute to overall mass and power. This is particularly the case in manifestations of absolute power and strength, where additional body mass will be clearly beneficial (Stanelle et al., 2021). While center players are often in a situation to express absolute strength and power (i.e., pushing the opponent from themselves, for example), this might also lead to a slightly higher body fat percentage than positions that prioritize speed and agility.

Finally, one highly specific biomechanical reason related to water polo sports should be briefly explained. Body fat can increase buoyancy. This added buoyancy can be advantageous for centers that need to maintain a strong and stable position in the water, especially when wrestling with opponents. However, one can argue that a higher body fat percentage can decrease swimming speed, and for that reason, more body fat would deteriorate center performance. However, although fast swimming is important in water polo, studies have highlighted that this capacity is more characteristic of outer players than centers (Kondric et al., 2012; Uljevic et al., 2014).

Anthropometric indices and performance-level

While the first set of analyses allowed us to identify the characteristics of three playing positions with regard to anthropometric status, the second set of analyses was performed to evaluate possible associations that may exist between anthropometric indices and players' performance levels. As introduced, the associations were established for each playing position separately, since differences in anthropometric status (please see previous discussion) would not allow meaningful analysis for the total sample. As evident, anthropometric characteristics were significantly associated with performance level when analyses were performed for inner and outer players, whereas there was no significant association between anthropometrics and the performance level of goalkeepers. We will discuss the latter finding first

Goalkeepers possess highly specific anthropometric characteristics, which have already been discussed from the perspective of their game duties, and there is no doubt that certain characteristics are highly beneficial and therefore could be associated with their performance level as well. However, there are several possible reasons for the lack of association between anthropometrics and performance level in the goalkeepers

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observed here. The first explanation is related to the fact that we sampled excellent teams from regions where the quality of water polo sport is high.

As a result, the goalkeepers we have sampled were well advanced in their quality, and what is also important, has already been selected. This means that at this competitive level and age, goalkeepers are already balanced in basic selective parameters, including anthropometrics. In other words, all goalkeepers observed in this study had all necessary anthropometric components that are important for successful goalkeeping (Platanou & Thanopoulos, 2002). Some differences between them still persist, but those differences are likely not the key factor for their differentiation in performance level, at least not the one we evidenced here. Therefore, it is probable that other qualities (i.e., explosiveness, reaction time) are more distinctive and play a significant role in differentiating between the performance levels of goalkeepers of this age and status.

The second explanation for the lack of association between anthropometrics and performance level in goalkeepers could be the relatively small number of participants and the unbalanced number of players in each observed performance group. Specifically, each team included 1--2 goalkeepers. Since we sampled players from two countries, the top-performance group consisted of only six players vs 13 players in high-level group. Simply statistically, the unbalanced number of players in two performance-level groups poses several problems. In most of the statistical analyses of differences, a smaller sample size dominates because the statistical power (i.e., the ability to detect a real difference between groups) is largely determined by the smallest group size, and having one much smaller group limits the overall power of the analysis. Additionally, statistical tests assume equal variances across groups. Unequal group sizes make the tests more sensitive to violations of this assumption, potentially leading to inaccurate results (Huck, 2008).

The performance level of the centers is determined by specific anthropometric structures, including long body segments (i.e., body height and arm span), large chest circumferences, and lower levels of body fat. Inner players in water polos have specific game duties, which are naturally accompanied by a very specific anthropometric status, as already discussed. This refers primarily to the need for them to be efficient in the contact game but also to manage to control space relatively well owing to their longer limbs (Uljevic et al., 2014). While the importance of body length has already been discussed when we overviewed the differences among playing positions, in the following text, we focus on other significant predictors of performance level in centers.

What is specific for centers in modern water polo is the need to move relatively well, regardless of the fact that swimming is not the main requirement of their game (Kontic et al., 2017). The circumference of the chest directly determines the vital capacity of young water polo players. Increased vital capacity not only increases working capacity under conditions of repeated anaerobic work but also clearly directly affects the amount of air in the lungs and total lung capacity and indirectly affects a player's buoyancy. In this way, the player is in a better position to accomplish his tasks and is enabled to work more efficiently, whether it is in attack or defense.

A larger chest implies several other factors that may be beneficial for centers. For example, a strong upper body, including the chest muscles, provides the power needed to hold off defenders, create space, and receive passes. Additionally, the chest muscles are involved in generating force for throwing the ball, allowing centers to shoot with greater velocity and accuracy. A larger chest volume often correlates with a broader overall physique. This increased body mass and wider base can enhance stability in the water, making it harder for defenders to push the center off balance.

Centers spend a significant amount of time treading water, often while wrestling with defenders (Kondric et al., 2012). A strong upper body, including well-developed chest muscles, helps with more efficient treading and reduces fatigue. Finally, water polo matches are physically demanding. Greater muscle mass in the chest and upper body can provide more endurance and resistance to fatigue, allowing centers to perform at a high level throughout the game. Certain psychological factors could be associated with better performance in centers with larger chests. First, there is no doubt that a physically imposing presence, including a large chest, can intimidate opponents and give the center a psychological edge. Moreover, feeling strong and physically capable can increase a center's confidence, which can positively influence its performance.

In explaining this correlation between body fat and performance level in outer players, it is important to highlight once again that water polo is a physically demanding sport that requires a combination of strength, speed, agility, and endurance (Uljevic et al., 2013). For outer players, who are primarily involved in swimming, passing, and shooting, maintaining low levels of body fat is crucial for optimal performance for several reasons.

The first reason is related to specific conditioning capacities and their importance for outer players. Excess body fat increases drag in the water, slowing down swimming speed and making it harder to change direction quickly (Dopsaj et al., 2020). Leaner players experience less resistance, allowing them to move more efficiently and react faster to the dynamic flow of the game. Additionally, lower body fat translates to a higher muscle-to-fat ratio, which improves acceleration and quick bursts of speed needed for sprints, steals, and defensive maneuvers. The fact that carrying excess weight (e.g., more body fat) requires more energy and oxygen should not be underestimated. Therefore, leaner players utilize oxygen more efficiently, allowing them to sustain high-intensity efforts for longer periods without fatiguing.

Another important mechanism is thermoregulation. While water polo matches can be long and intense, they generate significant body heat. A lower body fat percentage allows for better heat dissipation, preventing overheating and maintaining performance levels (Rech et al., 2021). This is particularly important for outer players since those players spend more time in the game (i.e., they are not substituted often as centers). Furthermore, excess body weight (i.e., ballast mass as a result of body fat) places extra stress on joints, increasing the risk of injuries. Leaner players are less prone to joint problems and can recover faster from physical exertion. Owing to the necessity of swimming for longer distances during match and training, this mechanism is more specific for outer players than for other playing positions.

Limitations and strengths

This was a cross-sectional study; therefore, causalities cannot be definitively interpreted. For example, there is a certain possibility that body fat level is a result of specific game duties and training characteristics for certain playing positions (i.e., longer swimming distances can reduce body fat). Therefore, prospective studies are needed to identify cause−effect relationships more specifically. This study highlighted only anthropometrics and their possible associations with the game position and performance level of water polo players.

The sample of participants consisted of high-level players, and performance levels included the identification of differences between groups of highly successful players. Therefore, this is one of the rare studies where analyses allowed the identification of factors that contribute to the differentiation of high-level and top-level youth players. Additionally, the sample of variables included a comprehensive set of anthropometric variables, and consequently, the specific anthropometric structure for each playing position and performance level was clearly identified.

Conclusion

The anthropometric variables did not distinguish goalkeepers according to their performance level. Most likely, the goalkeepers in this study were already selected on the basis of necessary anthropometric and body-built attributes, and in this stage of their sport careers, other indices are more important in determining their quality.

Tallness, length of body segments, and lower values of body fat are found to be significant predictors of success in outer players. Therefore, the body height and length of body segments should be used as selection parameters for this position in the water polo. Moreover, body fat can be effectively reduced through an appropriate diet and specific types of training. Therefore, by optimizing their body composition, outer players can maximize their performance and contribute more effectively to their team's success.

While talent, skill, and tactical awareness are essential for all water polo players, body height, arm length, chest circumference, and lower body fat can provide physical advantage for centers. This highlights the importance of considering specified physical attributes in player selection and development, particularly for this demanding position.

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ORIGINAL SCIENTIFIC PAPER

Cognition and Sport: How Does Sport Participation Affect Cognitive Function?

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Abstract

Cognitive-executive functions are essential processes for daily activities, academic, occupational and sporting success, health and quality of life. One way to improve them is through regular participation in physical activities. The aim of the study is to assess the effect of sports training on cognitive-executive functions. A total of 328 boys (220 young soccer players and 108 boys without participation in sport training) aged 12.0–14.9 years performed tests to assess their cognitive-executive functions (Deary-Liewald task, Corsii block test, Trail Making test). Two Way ANOVA was used to evaluate the significance of differences in cognitive functions in terms of two factors - sport (sporting vs. non-sporting boys) and age (12, 13 and 14-year old boys) and their interaction (group*age). ANOVA showed a significant effect of sport (in favour of soccer players) and age (increasing performance due to age in the soccer players group, ambiguous results in the non-sporting group) in the Deary-Liewald task assessing simple and choice reaction time. There were no significant effects of the observed factors in the Trail Making test and Corsii block test tasks. No interaction effect was demonstrated in any of the cognitive-executive tasks. The results indicate the influence of age and training process, especially in sports games, on reaction abilities. Short-term memory and visual control, perception, working memory, and cognitive flexibility are not significantly affected by participation in sport.

Keywords: *soccer players, non-sporting boys, simple reaction time, choice reaction time, visuospatial working memory, speed of visual search*

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Introduction

Physical activity is essential not only for physical but also mental health (García-Hermoso et al., 2021). Positive neurophysiological consequences of PA have been described by Cirrik & Hacioglu (2018), who referred to the increased level of hippocampal neuroplasticity due to exercising.

A direct positive correlation between PA and neurophysiological characteristics, including cognition, has been indicated by several studies. Specifically, PA can positively influence attention (Moratal et al. 2020), executive functions (Hillman et al., 2009), as well as academic achievements (Vaquerizo, 2022). It is also important to distinguish between acute PA and long-term (chronic) PA. Festa et al. (2023) describe that acute PA induces a transient response, whereas long-term and regularly performed PA produces a long-lasting effect.

In the context of long-term and regular PA, different ef-

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fects can be observed in relation to the nature of the activities. Closed-skill sports (gymnastics, running, etc.) are more predictable and stable, are less affected by environmental influences, and are performed according to predetermined movement patterns that are likely to require lower cognitive demands (Gu et al., 2019). In contrast, sports games (i.e. soccer, badminton, etc.) and sports with a direct contact with an opponent (martial arts) involve open motor skills and thus the response to external situational demands and active decision-making are crucial (Gu et al., 2019), which may lead to increased demands on the level of cognitive function. In this sense, Möhring et al. (2022) reported that children practicing sports containing open-skill activities had higher cognitive engagement and the ability to respond flexibly to changing situations than children practicing sports with predominantly closed-skill activities. Therefore, intentional practice of team-based, strategic sports may also represent a transfer to enhanced performance on non-sport-related cognitive tasks (Rahimi et al., 2022). Differences in the level of cognitive and especially cognitive-motor skills were also identified with respect to performance. Positive relationships have been found between measures of executive functions (Vestberg et al., 2017), attention test (Verburgh et al., 2014) and sports performance in youth soccer players. Differences between elite and sub-elite players were particularly evident at the highest age groups (Ehmann et al., 2022). Based on these findings, the difference in cognitive functions may be even more significant when comparing the sporting and general populations. Verburgh et al. (2016) compared youth soccer players with non-athletic children and found out that elite players outperformed sub-elite players and non-athletes in terms of inhibition, short-term memory, and working memory, while non-athletes were outperformed by sub-elite soccer players, as well. Children's participation in organized sports activities increases their fitness, and children with higher levels of fitness and coordination have been shown to have higher levels of attention and memory performance.

These theories suggest that children's long-term physical and sports activity may contribute to improving the quality of children's cognitive function; therefore, we hypothesize that children participating in organized sports training in soccer at the age of 12-14 years will perform better on tests of cognitive-motor functions (i. executive function; ii. visuospatial working memory; iii. speed of visual search and executive function) compared to the population without participation in organized sport activities.

Methods

Participants and design

The research was conducted as a two-group two-factor nonrandomized cross-sectional study. A total of 328 boys aged 11.8-14.9 years were divided according to their participation in organized physical activities into sporting and non-sporting group. Healthy adolescents who did not exhibit impaired mental functioning or medically identified cognitive decline were included in the research. In terms of decimal age, participants were divided into three age groups of 12-, 13- and 14-year olds with respect to the factor of sports activity, applying decimal age grouping (example 12.0 - 12.99 y.). Detailed demographic data for the groups of participants divided in terms of sport activity factor and age are presented in Table 1. The sporting group consisted of young talented soccer players (n = 220) and testing was carried out during the competitive season. They participated in an organized training process 3-4 times per week and played one match during the weekend, with a total load of 6-8 hours during the week. The training age of the players ranged from 4.0 - 7.5 years. The non-sporting group consisted of 108 boys who indicated in the demographic surveys that they did not participate in sports, did not engage in organized physical activity, or were included in it for less than half a year, as well as participants who practiced sports activities that did not include an element of systematic training (e.g. firefighting, skateboarding, riding a scooter, etc.).

Table 1. Demographic characteristics of research sample (mean ± SEM [95 % CI])

sport_group	Age_group	n	Age (y)	BW (kg)	BH (cm)	BMI (kg.m-2)
Sporting	12 y.	87	12.6±0.03 [12.5-12.6]	47.2±1.02 [45.2-49.3]	157.3±0.83 [155,6-158,9]	19.0±0.31 [18.4-19-6]
	13 y.	51	13.4±0.04 [13.3-13.4]	50.2±1.37 [47.4-52.9]	162.9±1.26 [160.4-165.5]	18.8±0.35 [18.1-19.5]
	14 y.	82	14.6±0.03 [14.5-14.6]	60.8±1.15 [58.5-63.1]	173.1±0.80 [171.4-174,8]	20.2±0,29 [19.7-20.8]
Non-sporting	12 y.	59	12.3±0.06 [12.1-12.4]	45.4±0.90 [43.6-47.2]	156.8±1.02 [154.7-158.8]	18.4±0.27 [17.9-18.9]
	13 y.	29	13.5±0.06 [13.3-13.6]	51.6±1.95 [47.6-55.6]	161.0±1.82 [157.3-164.7]	19.8±0.53 [18.7-20.9]
	14 y.	20	14.3±0.06 [14.2-14.4]	60.8±3.29 [53.9-67.7]	174.3±1.42 [171,4-177.3]	19.9±0.93 [18.0-21.9]

Note. BW - body weight; BH - body height; BMI - Quetelet's index

Variables

The study variables included somatic parameters (body height, body weight, BMI) as a part of description of the groups of participants and variables describing cognitive function (decision-making level, visuospatial working memory, visual screening ability and executive speed) divided to data subgroups in context of sport activity participation (sporting/non-sporting group) and age (12, 13, 14 y. old).

Diagnostic procedures were performed by individual participants on the same day always in the morning between 8:00 AM and 1:00 PM, maintaining the chronological order of the tests as listed below. Between each test item assessing cognitive function, a rest interval of 3-5 min was maintained corresponding to the time required to record the test result and prepare the next test item. Prior to the examination of cognitive ability level, demographic data were tested, namely body height with the accuracy of 0.1 cm using a Seca 217 stadiometer (SECA, Ham-

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burg, Germany) and body weight with the accuracy of 0.1 kg using an InBody 230 bioimpedance body composition analyser (Biospace Co., Ltd.; Seoul, Korea). BMI was calculated using a standard formula of body weight (in kg) divided by the square of body height (in m). Decision-making levels were assessed from the results of the Deary-Liewald task (Deary et al., 2010), including the measurement of simple (SRT) and choice (CRT) reaction time. To assess the visuospatial working memory, Corsi Block-Tapping test (Kessels et al., 2000). Speed of visual screening ability and executive functions were evaluated using Trail Making Test TMT-A a TMT-B (Tombaugh, 2004). All tests were performed by the test subjects alone in a quiet room with a trained examiner present, minimizing outside distractions.

In the Deary-Liewald SRT task, a single white square is presented in the center of the screen against the blue background. Whenever a black "X" appears within the square, a subject must respond as quickly as possible by pressing a spacebar key on a standard keyboard with the index finger of their dominant hand. The computer randomly generates 20 stimuli and the average reaction time is summarized in the results. In the CRT task, there were four stimuli and participants had to press the button that corresponded to the correct response. Four white squares ordered in a row are presented in the center of the screen. A black "X" appears in one of the squares per trial, and participants must indicate the correct answer by pressing one of the four keys, each corresponding to one of the spatial positions of the squares on the screen. From the leftmost to the rightmost square position, the following keys had to be pressed, respectively: the "z" key with the left middle finger, the "x" key with the left index finger, the "," key with the right index finger, and the "." key with the right middle finger (Peskar et al., 2023). A total of 40 temporally and positionally randomized stimuli were generated. Both SRT and CRT tasks were preceded by training trials consisting of 9 stimuli.

In the CORSI Block-Tapping task, nine pink squares are randomly positioned on the screen and (some of them) flash yellow in a certain order (different each run). A participant is instructed to repeat the observed sequence by clicking on the squares in the same order as presented before. With each iteration, the sequence is becoming longer, starting with 2 and increasing by one each time. If a mistake is made, a second trial with the same sequence-length but different square distribution is offered. The task is finished after two consecutive fails or when the longest sequence of 9 items is successfully demonstrated. The score reflects the longest correctly reproduced sequence and ranges from 2-9 (Peskar et al., 2023).

Trail Making Test Part A (TMT-A) is based on time needed to connect an array of 25 numbers in ascending order randomly distributed on a sheet of paper, by drawing a continuous line between them as quickly and accurately as possible. In the TMT-B, participants are required to connect an array of both numbers and letters in alternating ascending order (1, A, 2, B, 3, C, …) with the same emphasis on speed and accuracy (Hagenaars et al., 2018). In both versions, the result is a score in the form of the time taken to complete the prescribed task.

Two-way analysis of Variance (ANOVA 2x3) was used to assess the effect of group factor (sporting/non-sporting group) and age (12-, 13-, and 14-years old group) and their interaction on the level of selected cognitive abilities. To check the condition of normal distribution of research data for the use of Two-way ANOVA, rank transformation of raw values of the observed characteristics was used and the Shapiro – Wilk test showed violation of normality (nonpublished data). Levene's test was used to assess the equality of variances of the dependent variable between groups. The effect size of the observed factors was evaluated using Eta squared (η2). Multiple comparisons of means were performed using a LSD post hoc analysis. Statistical significance was assessed with a 5% probability of incorrectly rejecting the null hypothesis ($\alpha = 0.05$). Statistical analyses were performed using IBM SPSS Statistics software, version 20 (IBM SPSS Inc., Chicago, IL).

Results

Table 2 shows the results of the ANOVA in the context of the observed factors of sports activity and age of adolescent boys. Table 3 presents the values of the descriptive statistical analysis of the observed variables of cognitive functions for each subset of participants.

Table 2. Results of assessment of the influence of sports activity and age on the level of cognitive abilities of adolescents (ANOVA 2x3)

Test	Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
	group	64483.7	1	64483.67	7.822	0.005	0.024
SRT	age	80263.6	2	40131.78	4.868	0.008	0.029
	group*age	28784.1	2	14392.04	1.746	0.176	0.011
	group	45532.1	1	45532.14	5.369	0.021	0.016
CRT	age	108933.4	2	54466.69	6.423	0.002	0.038
	group*age	4780.8	2	2390.38	0.282	0.755	0.002
	group	16185.5	1	16185.54	1.998	0.158	0.006
CBT	age	22152.1	2	11076.05	1.368	0.256	0.008
	group*age	27460.8	2	13730.39	1.695	0.185	0.010
	group	333.8	1	333.80	0.038	0.845	0.000
TMT-A	age	52607.6	2	26303.78	3.004	0.051	0.018
	group*age	21297.6	2	10648.81	1.216	0.298	0.007
	group	3385.2	1	3385.15	0.383	0.536	0.001
TMT-B	age	41563.2	2	20781.61	2.354	0.097	0.014
	group*age	11992.6	2	5996.29	0.679	0.508	0.004

Note. df – degree of freedom; F – value of ANOVA testing criterion; Sig – p value; SRT – simple reaction time; CRT – choice reaction time; CBT – Corsi block tapping test; TMT-A – trail making test version A; TMT-B – trail making test version B

For none of the cognitive ability tests, two-way ANOVA (2x3) showed a significant effect of the interaction of the observed factors group*age (p>0.05). Partial Eta squared achieved values interpreting a small effect size of the studied factors of age and sports activity on the level of cognitive abilities (Table 2). The age factor proved to be statistically significant in the decision-making levels in the simple and choice reaction time tests (p<0.05). However, there were no statistical differences between age groups in the level of visuospatial working memory (CBT) and speed of visual search and executive function (TMT-A and TMT-B), regardless of the sports activity performed.

Similarly, the participation in organized sports training was shown to be a significant factor only in the comparison of executive functions in SRT and CRT tests (p<0.05), when soccer players performed better in all age groups (Table 3).

Table 3. Results of aggregated descriptive characteristics of cognitive abilities of adolescents assigned to groups according to sport activity and age (presented as mean±SEM [95% CI])

Group	Age	SRT (ms)	CRT (ms)	CBT (no)	TMT-A (s)	TMT-B (s)
sport	12 y. old	291.5±2.8 [286.0-297.0]	485,6±7.7 [470.5-500.7]	5.29±0.12 [5.06-5.52]	31.1±0.88 [29.4-32.9]	68.6±2.8 [63.0-74.1]
	13 y. old	282.5±3.6 [275.7-290.0]	467,4±10.0 [447.0-487.1]	5.78±0.15 [5.48-6.08]	28.5±1.15 [26.2-30.8]	68.9±3.7 [61.7-76.1]
	14 y. old	274.7±2.9 [269.1-280.4]	463,0±7.9 [447.4-478.5]	5.77±0.12 [5.53-6.00]	27.4±0.91 [25.6-29.2]	59.7±2.9 [54.0-65.4]
non-sport	12 y. old	295.1±3.4 [288.5-301.8]	520,2±9.3 [501.8-538.5]	5.42±0.14 [5.14-5.70]	29.0±1.07 [26.9-31.1]	69.3±3.4 [62.6-76.0]
	13 y. old	289.7±4.8 [280.2-299.2]	475,2±13.3 [449.1-501.4]	5.45±0.20 [5.05-5.85]	29.3±1.53 [26.3-31.5]	64.7±4.9 [55.1-74.3]
	14 y. old	289.3±5.8 [277.8-300.7]	479,4±16,0 [447.8-510.9]	5.40±0.24 [4.92-5.88]	27.9±1.84 [24.2-31.5]	62.0±5.9 [50.4-73.5]

Note. SEM – standard error of mean; 95% CI – 95% confidence interval; SRT – simple reaction time; CRT – choice reaction time; CBT – Corsi block tapping test; TMT-A – trail making test version A; TMT-B – trail making test version B

Discussion

The results of the study indicate higher levels of executive function in the form of simple and choice reaction (Deary-Liewald task) in individuals performing organized physical activity across the observed age groups. On the other hand, there were no differences in visuospatial working memory (Corsi block test) as well as in visual screening ability and executive speed (TMT-A and TMT-B). The influence of the age factor was manifested in the group of sporting individuals (in the group of football players), where the level of the observed cognitive functions gradually increased, with the exception of the comparison of groups 13- and 14-years old in visuospatial working memory, where stagnation of performance was recorded. On the contrary, in the group of non-sporting individuals, the results are heterogeneous without the possibility of determining trends of development due to the influence of age."Simple and choice reaction time (Deary-Liewald task)

Reaction time is conditioned by the speed of perception, the conduction of impulses to the controlling organs along afferent pathways and then to the executive organs in the periphery along efferent pathways; in summary, the speed of task execution is conditioned by the level of mental processes, especially thinking. Reaction time is also an important factor influencing athletic performance in team sports, and by performing sporting activities, cognitive stimulation can be achieved in relation to reaction time (Vidal et al., 2015). Consistent with the above premise, in terms of mean SRT values, better performances were observed in all defined age groups of soccer players (Table 3). The differences in simple reaction time between the sporting and non-sporting population have been also confirmed in studies by Vestberg (2017) or Badau et al. (2024).

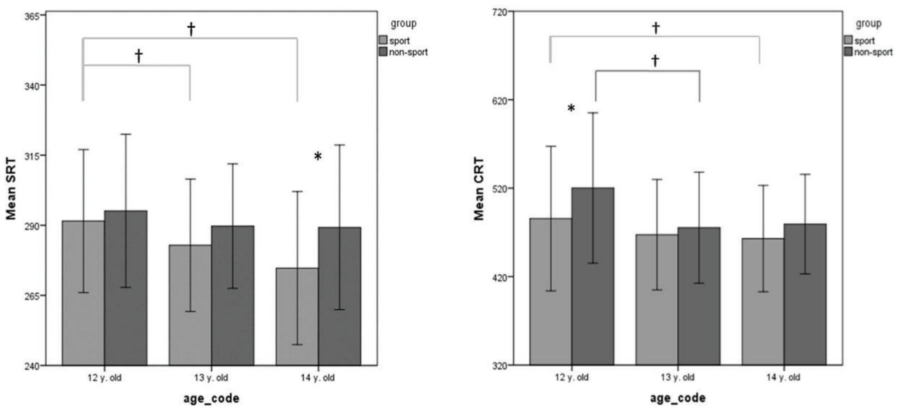

Figure 1. Graphical comparison of performance in simple reaction time (SRT) and choice reaction time (CRT) tasks in relation to sports activity and age with identified significant differences based on LSD post hoc analysis († significant differences between age groups; * significant differences between soccer and non-sporting group)

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Significant differences in SRT were only demonstrated in the group of 14-year olds. The reasoning can be found in the structure of the required activity in the test. As the test used was nonspecific in the context of the physical activity performed, the daily routine activities seem to generate a sufficient number of stimuli to ensure a relative equality of performances between sporting and non-sporting individuals at the beginning of the adolescent period. This assumption has been confirmed by observing the differences in terms of age. In the group of soccer players, the difference in the level of simple response between age groups was significant (group 12 vs. 13 y. old, similarly for 12 vs. 14 y. old), in contrast to the group of non-athletes (Figure 1). These results may support the theory of a positive effect of long-term physical activity with a predominance of open skills on simple reaction time.

The choice or cognitive reaction time involves the selection or combination of some tasks in the shortest possible time in relation to the nature, complexity, and intensity of the stimulus (Quoilin et al., 2019). The recorded changes indicated the same trend as in the SRT evaluation. Better performance of soccer players in the CRT was captured across the whole spectrum of age groups tested. However, in contrast to the SRT, the sports activity factor proved significant in this test only for the youngest group of 12-year-old boys. It appears that the impact of training containing CRT stimuli, typical for team sports such as football, is predominant especially in younger age groups. At the age of 12 years, soccer players have been involved in controlled training for approximately 5 years. With increasing age, non-sporting individuals are more frequently exposed to stimuli requiring a response to an unanticipated stimulus in both school and out-of-school environments (in the context of both the physical education content and greater independence in extracurricular physical or other activities) and thus the distinctions between trained and untrained individuals become blurred. In both groups (sporting and non-sporting group), increasing levels of CRT with age were observed. While in the non-sporting group, Figure 1 identifies a sharp increase in performance when compared 12- and 13-year olds with confirmation of significance and subsequent stagnation of performance, in the sporting group, performance improved gradually in the context of age with significant changes in CRT levels in a two-year interval (comparison of 12- and 14-year olds). The results of a group of soccer players are in line with Beavan et al. (2020), who confirmed a positive relationship between age and executive functions in a large cohort of elite youth soccer players. Similarly, Hielmann et al. (2021) reported increasing levels of CRT across the U12 - U17 categories.

Visuospatial working memory (Corsi Block-Tapping test)

Working memory is described as the ability to temporarily store and process information, and as reported by Gathercole et al. (2004), its level increases linearly from childhood to adolescence. This is consistent with results in a group of soccer players, where in the Corsi block test results, an increasing level of short-term working memory with increasing age (both in terms of means and lower limit of performance 95% CIs) were observed. In the case of non-athletes, results of the age comparison are not clear. When comparing groups in the context of the physical activity factor, higher levels of short-term working memory in soccer players compared to non-sporting boys were found across all age groups (Table 3). There are studies that confirm the positive impact of physical activity on working memory (Samuel et al., 2017; Hsieh et al. 2017; Drozdowska et al., 2021). However, the differences captured were not large enough to be confirmed by statistical significance or by effect size (Table 2).

Speed of visual search and executive function (TMT-A and TMT-B)

"Lower order" cognitive processes are necessary for basic information processing. In the TMT-A test, with the exception of the 12-year old group, better results were found in soccer players compared to non-athletes. Our results are consistent with studies by Alves et al. (2013) and Nakamoto & Mori (2012), where difference in lower-order cognitive functions between the sporting and non-sporting population was not confirmed. However, even in the TMT-B test, which is classified as a test of a higher-order cognitive process, no significant differences between soccer players and non-athletic peers were found. This result is contrary to the study by Huijgen et al. (2015), who in a group of slightly older soccer players (mean age ~ 15.3) confirmed a difference in "higher-order" cognitive processes, especially in metacognition and cognitive flexibility, in terms of the level of sporting activity (elite and sub-elite soccer players), thus, figuratively, we assume there also would be a difference in comparison to the non-sporting population.

Soccer players gradually improved in TMT-A as they got older, but the differences are minimal. In the case of non-athletes, the result does not allow an age trend to be determined. Overall, no significant differences in this test in terms of either age or sport activity were observed. In the TMT-B test, a performance plateau followed by a sharp rise in performance by age 13 was recorded in athletic subjects. In the non-sporting group, performance in the TMT-B test improved with age. In summary, it can be concluded that age has a positive effect on speed of visual search and executive functions regardless of sport activity in adolescent boys.

Several limitations have been identified in the study. The first is the non-randomized cross-sectional study design, which may be prone to selection bias. However, we do not anticipate an effect on the results of this study. The second is the group size of the primarily non-sporting population. Our study group represents only a small proportion of the total cohort of non-sporting individuals in the observed age range. Therefore, the interpretation of the results is limited to the group tested and the generalisation of the study outcomes may not be adequate. A third limitation is the selection of tests assessing cognitive ability with respect to a specific sporting population (soccer players). The tests implemented are generic without corresponding specificities to the demands of soccer. On the other hand, it was necessary to choose diagnostic procedures that would not be limiting for the non-sporting group and which execution would not be dependent on the level of motor prerequisites. Last, the motivation of the participants is an essential condition for testing cognitive abilities. In the diagnostic process, participants, regardless of group affiliation, were encouraged to take the tests with as much focus and effort as possible to achieve the highest possible result.

Conclusion

The results indicate the influence of age and training process, especially in sports games, on reaction abilities. Short-term memory and visual control, perception, working memory, and cognitive flexibility are not significantly affected by participation in sport.

The test protocol used to assess general cognitive function appears to be insufficient to detect differences in cognitive function between individuals with different levels of physical activity. Previous research also suggests an improved level of cognition in individuals performing aerobic activity compared to non-sporting individuals. Therefore, we recommend that research should focus on monitoring cognition in groups with different types of physical activity. In addition, for further follow-up in this area, it would be advisable to include methods involving higher levels of motor expression in the performance of test items.

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Disclosure statement
The authors declare that there is no conflict of interest with any financial organization in relation to the research problem discussed in the manuscript.

Ethical Approval Information
Measurements were taken according to the ethical standards of the Declaration of Helsinki. The research was approved by Ethical Commission of University of Prešov (ECUP-032023PO). Participation in the study was fully voluntary and anonymous. A participant’s legal guardian received a written description of the study procedures before testing and submitted a written informed consent to participate in this study.

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ORIGINAL SCIENTIFIC PAPER

Association between parental physical activity and motor skills in their preschool children

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Abstract

Young children often observe and emulate the actions of adults, whom they look up to as role models. Considering that parents have an influence on their children at an early age, the aim of this study was to determine whether there is a correlation between the physical activity of parents and the motor skills of their children of preschool age. The study included 1212 boys and girls and their parents (N=2287) from Croatia. Parents completed the "Single item physical activity" questionnaire (SIPA) for research purposes which assessed their physical activity. Preschool children were tested with "Bruininks-Oseretsky Test of Motor Proficiency - Second Edition" (BOT-2) and "Test of Gross Motor Development - Second Edition" (TGMD-2), which assessed their motor skills. Multinomial regression analysis showed a significant association between paternal physical activity and score in the TGMD-2 of their children. It is up to parents to encourage their children in physical activity, and thus the development of motor skills. In this way, children will create healthy habits and have a greater chance of being active throughout their lives.

Keywords: *kindergarten, motor abilities, maternal physical activity, paternal physical activity*

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Introduction

Motor skills represent movement structures that are learned from birth and applied throughout life in different life situations and activities (Sekulić & Metikoš, 2007). During early childhood, the learning of new movement skills is affected by the overall development in different areas, which are in mutual interaction: physical, cognitive and socio-emotional (Krstulović, 2018). It is necessary to facilitate the learning of motor skills in different developmental stages, particularly in early childhood thrughout enriched environments.

Physical activity and motor skills are connected by cause-and-effect relationships (Butcher & Eaton, 1989). Children and adults with a higher level of motor skills consequently have more chances and confidence to engage in physical activity in the future compared to people and children with a lower level of motor skills and abilities (Wrotniak et al., 2006). This is why physical activity and the development of motor skills are extremely important for overall human development and health in life.

Young children often observe and emulate the actions of adults, whom they look up to as role models. Through imitation, children acquire valuable skills and behaviours through childhood. During early childhood, adults play a crucial role in shaping a child's behavior. Specifically, parents have the

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greatest influence on their child's motor development, physical activity levels, and formation of habits related to exercise (Kimiecik et al., 1996; Brustad, 1993; Kimiecik & Horn, 1998). This is because the family is the child's primary environment during their formative years, providing opportunities for parents to guide their child's actions (Kimiecik et al., 1996). Parents have control over their child's activities and are responsible for how their child spends their time (Shartaya et al., 2006). As such, parents should strive to model healthy habits and encourage physical activity to promote a healthy lifestyle for their child.

Previous research shows that various parental influences may play an important role in shaping physical activity of their preschool children. Two recent meta-analysis show various parental factors significantly related to child's physical activity such as parental support for physical activity (e.g., encouragement, facilitation, and modeling of physical activity), parental monitoring, parental physical activity and parental participation in physical activity with their children (Su et al., 2022; Arts et al., 2023).

Given the association between higher physical activity and better motor proficiency (Wrotniak et al., 2006; O'Neill et al., 2013; Xu et al. al., 2018), there is a possibility that the environmental factors that are associated with motor skill proficiency may be similar to those for physical activity. An older review by Sallis et al. (2000) showed that in 38%, of the 29 included studies, positive correlation was found between the physical activity of parents and the physical activity of their children 4-12 years of age. Cools and associates (2011) found in a large sample that fathers' physical activity level was positively associated with fundamental motor skills in preschool boys. Newer studies have failed to reproduce findings of parental physical activity relation to child's motor skills. The study of Barnett and associates (2013) found that none of the family factors (interaction, physical activity, confidence) were correlated with children's locomotor skills. Both studies found that environmental factors such as the having physical activity equipment at home was positively correlated with both locomotor and object control skills in children. In research of Paez and associates (2022) parental physical activity level does not appear to have a significant impact on their children's motor development level. On the other hand, physical activity level of parents was related to their children's body mass index and authors concluded that promoting physical activity among parents could be an effective way to prevent childhood obesity and to promote healthy lifestyle for both parents and children.

Given that previous research has established the connection between parental physical activity and their child's physical activity, it is assumed that the level of physical activity of parents will also affect the level of motor skills of children, the connection of which has not been sufficiently investigated so far.

Therefore, the aim of this research was to determine the association between the physical activity of parents and the motor skills of their preschool children.

Methods

Participants

1212 boys and girls aged 3 to 6 years and 2287 of their parents (1173 mothers and 1114 fathers) from different parts of Croatia participated in this research. Given that this research was part of a larger study, the sample is larger than the minimum recommended (Raosoft sample size calculator = 384). The average age of preschool children included in this research was 5.2 years. The children of preschool age who were included in this research attended state kindergartens that were chosen randomly for the purposes of the research. All children from randomly selected kindergartens participated in the measurements. In addition to preschool children, their parents also participated in the research.

Considering the current population census before conducting this research and considering the number of children attending kindergartens in different parts of the Republic of Croatia, the kindergartens that participated in this research were chosen by random selection. Agreements for participation were signed with the directors of the kindergartens, after which agreements were also signed with the parents for their children's participation in the research.

Measurements

For research purposes, parents filled out "Single item physical activity" questionnaires (SIPA), which uses a single question to assess the level of their physical activity (Milton et al., 2011). Data were obtained on the number of days in the previous week when the person engaged in at least moderate physical activity for a minimum of 30 minutes. Accordingly, the maximum number of days was 7, and the minimum number of days was 0 in physical activity. For the purposes of this research, we specifically analyzed the physical activity of mothers, especially fathers, but also the average activity of both parents together. The reliability of this questionnaire is r=0.72-0.82, while the validity is r=0.53 (Milton et al., 2011).

Children were measured with two batteries of tests: "Bruininks-Oseretsky Test of Motor Proficiency – Second Edition" (BOT-2) (Bruininks & Bruininks, 2005) and "Test of Gross Motor Development – Second Edition" (TGMD-2) (Ulrich, 2000). A short version of the BOT-2 test battery was used, consisting of 14 separate tests. This battery of tests showed high reliability (0.86 to 0.89) (Cools et al., 2009). 860 children of preschool age were measured with the TGMD-2 battery of tests in all 12 tests of which the battery consists of. Previous research has confirmed that the TGMD-2 has very good metric characteristics (Cronbach alpha .82 to .94) (Ulrich, 2000).

For the purposes of statistical analysis, the results of preschool children measured in this research in the TGMD-2 and BOT-2 tests were divided into 3 categories. For the TGMD-2 test, the results are divided into: category 1 (69-80 - bellow average), category 2 (81-105 - average) and category 3 (106-116 – above average). For BOT-2 the results are also divided into: category 1 (32-40 - bellow average), category 2 (41-57 - average) and category 3 (58-66 – above average).

Data analysis

Statistical analyses were performed using TIBCO Statistica v.13 software (TIBCO Statistica Inc, OK, USA).

The influence of predictors (maternal physical activity, paternal physical activity, and average parental physical activity) on criteria (trinomial criteria: bellow average – average – above average TGMD-2/BOT-2) we calculated multinomial regression, with Odds Ratio (OR), and 95% Confidence Interval (95%CI) reported. In multinomial regression above average achievement group on TGMD-2/BOT-2 was used as reference group.

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Results

Results of this research show that mothers were physically active for 2.78 days (σ=1.97) in a week. The most frequently obtained or dominant value for mothers was 2 days of moderate physical activity in the previous week. For fathers, the average physical activity was 3.13 days (σ=2.07). The dominant value for fathers was 3 days of moderate physical activity in a week. Average values for both parents show that mothers and fathers were physically active for 2.92 (σ=1,72) days in a week.

Table 1. Descriptive statistics of physical activity mothers, fathers and both parents

	MEAN	MODE	STD.DEV.
PAM	2.77	2	1.97
PAF	3.11	3	2.08
PABP	2.92	3	1.75

PAM - physical activity of mothers; PAF - physical activity of fathers; PABP – average physical activity of both parents; MEAN; STD. DEV. -Standard Deviation

The average value of standardized results in the BOT-2 test of preschool children included in this research is 48.95 (σ=8.61). Average value of the Gross Motor Quotient (TGMD-2 test) was 93.56 (σ=11.72). When we divide the TGMD-2 battery of tests into Locomotor Subtets and Object Control Subtest, we get average values of 9.76 (SSLS, σ=2.35) and 8.05 (SSOCS, σ=2.26).

Table 2. Descriptive statistics of motor skill in preschool children

	SS(BOT-2)	GMQ (TGMD-2)
MEAN	48.95	93.56
STD.DEV.	8.61	11.72

SS(BOT-2) – Standard Score(BOT-2); GMQ(TGMD-2)- Gross Motor Quotient

Figure 1. presents results of the multinomial regression calculated for trinomial criteria BOT-2 (Figure A) and TGMD-2 (Figure B). Multinomial logistic regressions for variables of parental physical activity were not significant when BOT-2 was observed as criterion variable (PAM: OR = 0.99, 95%CI: 0.96-1.03; OR = 0.98, 95%CI: 0.94-1.03; PAF: OR = 1.00, 95%CI: 0.97-1.03; OR = 1.01, 95%CI: 0.96-1.05; PABP: OR = 1.00, 95%CI: 0.98-1.02; OR = 0.99, 95%CI: 0.96-1.02) for bellow average and average group with in comparison to above average group, respectively (Figure A). Meanwhile, PAF was significantly related to TGMD-2 score in children, with lower likelihood of being groups in above average cluster for those children whose fathers were more physically active (OR = 0.94, 95%CI: 0.90-0.98) (Figure B).

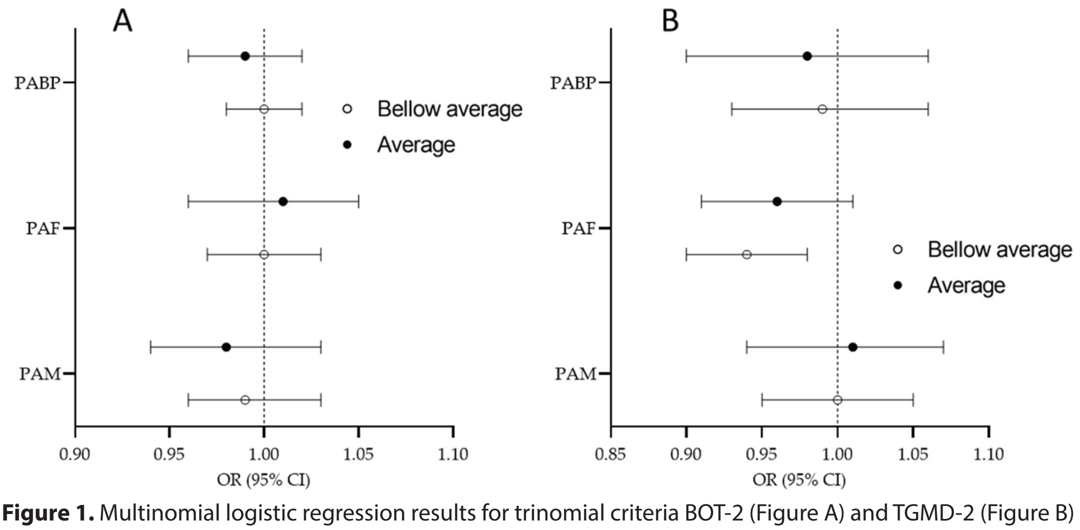

Figure 1. Multinomial logistic regression results for trinomial criteria BOT-2 (Figure A) and TGMD-2 (Figure B)
Legend: PABP – average physical activity of both parents, PAF – physical activity of fathers, PAM – physical activity of mothers

Discussion

Multinomial regression analysis showed a significant association between fathers physical activity and children's score in the TGMD-2 battery of tests (trinomial criteria) (Figure 1.).

Previous research shows that the level of parental physical activity can strongly influence their children's behavior (Xu et al., 2018) as well as significant positive correlation between parent's physical activity and children's physical activity and motor skills (Zecevic et al., 2010; Krmpotić & Stamenković, 2014; Shartaya et al., 2006). Also, a week but positive relationship between parents and child physical activity (PA) was found in review Petersen at al. (2020). Furthermore, earlier research showed that there is a positive correlation between children's basic motor skills and fathers' physical activity (Cools et al., 2011) as obtained by multinomial regression from this research.

Based on the obtained results, we can ask ourself why there is a association between fathers physical activity and childrens motor skills, and why is not the same with mothers. And the other guestion is why was the association shown only in the TGMD-2 and not in the BOT-2 test?

The reasons for that can be searched in the research of Krmpotić and Stamenković (2014), which showed that an equal percentage of mothers and fathers of the children involved in their research have participated in some sports in the past, however, mothers played sports on average for 6.29 years in their lifetime and fathers for 9.96 years in their lifetime. Therefore, mothers were more involved in dance, rhythmic gymnastics and handball, while fathers mentioned football and basketball as the most common activities.

If we know that the TGMD-2 battery of tests is more intended for the assessment of gross motor skills (such as running, galloping, throwing and catching the ball, kicking the ball with the foot, etc.) and if we also consider that mothers are throughout the day and during growing up of the children in general probably more busy in household work than the fathers, it is to be assumed that the physical activity of the fathers has a greater influence on the development of the children's motor skills, especially the gross ones, since we can also assume that fathers carry out activities with their children which are known to themselves.

Furthermore, the research Kamionka at al. (2023) also showed a greater influence of the fathers physical activity (PA) on the childs PA compered to the mothers. Namely, if mothers are active, children are 2.0 more likely to be active, and if fathers are active, then they are 3.5 more likely to be active.

That's why in this research we probably obtained exactly the association between fathers physical activity and children's results in the TGMD-2 battery of tests and not in the BOT-2 battery of tests, which more covers a part of fine motor skills.

Contrary to this study in the research by Paez et al. (2022) no significant correlations were found between the level of physical activity of parents and the motor skills of their children, but this research was conducted with children aged 8 to 10 and their parents, also using the same test (TGMD-2) to assess children's motor competence. We can assume that the results of Paez et al. (2022) differ from our results due to the age of the children involved in the research, namely, according to Sallis et al. (2002), as the child's age increases, parental influence decreases and the influence of their peers on physical activity increases.

Based on acquired knowledge, parents are one of the key models for the acquisition and improvement of children's healthy behavior. In fact, parents serve as role models for an active lifestyle and therefore it is important to highlight the importance of the role of parenting in connection with physical activity and basic motor skills during early childhood (Agard i sur., 2021).

Although parents are one of the main links in the process of forming and guiding a child in development, Hands (2012) points out that parents and educators sometimes react wrongly and do not focus enough to mother issues, if they exist, but simply classify the child as "non-sporty" type, lazy or clumsy, which in the long run can lead to problems of a physical, emotional, social or health nature. Piek et al. (2012) point out that early identification of possible problems in motor skills is crucial, not only because of work on improving motor skills but also because of health, intellectual, and psychosocial problems that can arise due to low motor skills with which the mentioned problems are related. Research by Liong et al. (2015), which dealt with the difference between the perception of children and parents and the actual performance of motor skills by children, showed that boys evaluate their actual performance well, while parents only evaluate manipulative skills in boys and locomotor skills in girls well. The authors, therefore, suggest interventions aimed at parents in order to learn how to recognize the good or bad performance of motor skills and thereby react in time and provide help to their child.

The authors point out that the period from the 2nd to the 7th year of life (the period of infancy and most of early childhood) is the period when basic motor skills develop the most (Gallahue, 1982; Sanders, 1992), and the stages of development can be divided into the initial, basic and mature stage. At the same time, a child at the age of 6 should reach the mature stage, for some fundamental motor skills like walking or running, moving accurately, efficiently, and coordinated (Božanić, 2011).

Children who have reached the mature stage of development move to the first stage of learning specific motor skills, while children who have not reached this stage have a limited possibility of progress in later stages (Gallahue & Donelly, 2003) as well as problems in interaction with the environment and with the quality of physical manipulation. (Pišot, 2018). Lippincott (2004), on the other hand, points out that parents must let the child learn motor skills when he or she is ready for it because sometimes rushing can cause frustration in the child. This is why it is necessary to educate parents to recognize a possible problem and to know what a child should be able to do at what age. Karković (1998) lists 15 types of parents and how each of these types, and their behavior, affect the child's attitude towards sports and the subsequent continuation of involvement in various sports and recreational activities throughout life. A common mistake of parents is interfering with the work of trainers and kinesiologists and placing high expectations on their child (Karković, 1998). Accordingly, Cools et al. (2011) found a negative correlation between preschool children's basic motor skills and parental perception of the importance of winning in physical activity.

From the above, it can be concluded that emphasizing winning and thereby creating pressure from parents toward children, creates children's aversion to physical activity, and if children do not acquire the habit of regular physical activity from an early age, this habit will be more difficult to take root at a later age. That is why it is important to take serious steps in solving this problem, starting with motivating and directing children to physical activity from the earliest age, when there is the greatest chance of adopting healthy lifestyle habits, and thus learning basic motor skills.

Limitation of this study is that the physical activity of the parents was assessed with a questionnaire. We believe that in some future research, more objective and accurate measuring instruments should be used to assess parents' physical activity, such as an accelerometer, which we believe would provide better information (level and intensity of parents' physical activity).

Conclusions

Parents undoubtedly have a strong influence on their children in the earliest stages of their growth and development. Parents are one of the most important people who serve as a „model" for children's behavior and learning. If a child acquires the habit and need for regular physical exercise in the

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earliest stages of his life, it is more likely that he will remain active in the later stages of his life. Also, if we know that physical activity and motor skills are connected by causal relationships (Butcher & Eaton, 1989; Graf et al., 2004; Wrotniak et al., 2006; Fisher et al., 2005; Williams et al. 2008; Kambas et al., 2012), then it is to be expected that more active children will have more opportunities to develop their motor skills to the level that is expected of them at a certain stage of life. Furthermore, an adequate level of motor skills will be useful to them throughout their lives, therefore it is extremely important to encourage children to be physically active from an early age, and parents certainly have one of the most important roles in this effort.

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Effect of Caffeine Ingestion Before or After Muscle Damage on Delayed Onset Muscle Soreness: A Meta-Analysis of Randomized Controlled Trials

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Abstract

Objective: The present study aimed to conduct a meta-analysis based on available randomized controlled trial data to evaluate the effect of pre- or post-exercise caffeine ingestion on pain in individuals with Delayed onset muscle soreness. Methods: PubMed, Web of Science, Scopus, and SPORTDiscus databases were systematically searched (from inception to December 2023) to identify randomized controlled trials evaluating the effectiveness of caffeine on muscle pain before and after exercise damage. Visual analog scale was determined as the outcome measure. To compare the means and calculate the overall effect size "Cohen's d" coefficient was used. Cochran Q test and I^2 statistics were used to evaluate heterogeneity between studies. Results: Eight randomized controlled trials were analyzed as part of the meta-analysis. 5-6 mg/kg caffeine did not significantly reduce visual analog scale at 24 hours when ingested pre-damage ([Standardized Mean Difference (SMD) = -0,022, p=0,920, I^2 : 0%]), and VAS at 24, 48, and 72 hours when caffeine was used post-damage ([SMD = -0,568, p=0,135, I^2 : 75,89%], [SMD = -0,169, p=0,747, I^2 : 78,61%], [SMD = -0,181, p=0,523, I^2 : 2,78%], respectively). Conclusion: Consuming 5-6 mg/kg of caffeine before or after muscle damage is not sufficient to reduce delayed onset muscle soreness related muscle pain. The potential effectiveness of 3mg/kg caffeine in preventing or reducing delayed onset muscle soreness pain seems promising. More studies are needed to evaluate caffeine at different doses and periods.

Keywords: *caffeine, muscle pain, muscle soreness, visual analog scale, meta-analysis*

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Introduction

Delayed onset muscle soreness (DOMS) commonly develops following repeated high-intensity eccentric muscle contractions or participation in unfamiliar exercises. DOMS shows symptoms like pain, muscle and joint stiffness, muscle tenderness, swelling, decrease in muscle strength, and decrease in exercise capacity for up to 1 week (Lewis et al., 2012). One of the most commonly accepted explanations for exercise-induced muscle damage is the substantial mechanical stress exerted on muscle myofibrils during eccentric contractions and changes in metabolic activities leading to loss of cellular homeostasis induced by exercise (Clarkson & Sayers, 1999).

DOMS is considered a grade 0 muscle injury according to the British athletics muscle injury classification and is frequently seen in both elite and amateur athletes (Cheung et al., 2003; Pollock et al., 2014). Treatments such as non-steroidal anti-inflammatory, cold water immersion, stretching, massage, exercise, therapeutic ultrasound, acupuncture, and electrical stimulation have limited effectiveness on muscle pain (Cheung et al., 2003; Hübscher et al., 2008). In addition to these interventions, dietary supplements such as caffeine (Hurley et al., 2013) and ginger (Matsumura et al., 2015) which have anti-inflammatory actions, are used for the treatment of DOMS. Caffeine has been shown to increase IL-10 levels during the inflammation process induced by exercise and to support the anti-inflammatory response by reducing oxidative stress. (Tauler et al., 2013, 2016). Caffeine acts on the nervous system by blocking central adenosine A2B receptors and afferent peripheral sensory pathways A2A (Sawynok, 1998). This action can alter pain intensity and may serve as a helpful adjunct in managing both pain and headaches (Derry et al., 2014). Pre-exercise caffeine ingestion decreases the perception of pain, reduces the degree of perceived exertion, and increases exercise capacity (Doherty et al., 2004). Post-exercise caffeine ingestion increases muscle glucose levels, Calcium2+/calmodulin-dependent protein kinase phosphorylation, new glycogen synthesis rate and glycogen accumulation (Pedersen et al., 2008). Also post-exercise caffeine intake has been reported to delay autonomic recovery by causing increased sympathetic nerve activity (Bunsawat et al., 2015).

Literature review reveals several randomized controlled studies that have investigated the impact of caffeine on DOMS-related pain, with varying findings (Al-Nawaiseh et al., 2022; Chen et al., 2019; Hurley et al., 2013; Maridakis et al., 2007; Santos-Mariano et al., 2019). Some results showed that caffeine intake leads to significantly lower pain levels in the following days compared to placebo (Hurley et al., 2013; Maridakis et al., 2007). In contrast, some studies found caffeine ineffective on pain scores in DOMS (Al-Nawaiseh et al., 2022; Santos-Mariano et al., 2019). Recently, an important meta-analysis study evaluated the effects of caffeine on DOMS (Muljadi et al., 2021). Despite the potential differences in caffeine's effects when used before or after exercise, this meta-analysis analyzed studies without making a distinction between caffeine use before or after exercise (Muljadi et al., 2021).

This study aimed to perform a meta-analysis using data from existing randomized controlled trials to more clearly assess the impact of pre- or post-exercise caffeine consumption on pain in patients with DOMS.

Methods

This meta-analysis was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

Literature Search Strategy

Muscle pain associated with DOMS was evaluated by conducting a literature search using electronic databases such as PubMed, Scopus, Web of Science, and SPORTDiscus to identify relevant articles assessing the impact of caffeine supplementation. The database search was performed from the earliest date to December 2023 without language filtration. The following keywords were used without any automatic filters to find the relevant articles: (caffeine) AND ((delayed onset muscle soreness) OR (DOMS) OR (muscle damage) OR (exercise-induced muscle damage) OR (EIMD) OR (muscle soreness)) AND ((VAS) OR (visual analog scale) OR (pain)).

Inclusion and Exclusion Criteria

Quasi-randomized or randomized and controlled trials published in English that used a crossover or parallel design were included in this meta-analysis. Inclusion criterias were: (1) studies compared caffeine with a placebo pre- or post exercise-induced muscle damage; (2) studies used a protocol designed to exercise-induce muscle damage (EIMD); (3) studies included in the analysis reported at least one measure of muscle soreness index following exercise-induced muscle damage, assessed at baseline and again at 24, 48, and/or 72 hours post-exercise. Exclusion criterias were: (1) studies without a control group; (2) studies used drugs, other supplements, and diet; (3) participants of the studies having any metabolic, or musculoskeletal disorders; (4) animal studies, case reports, letters to the editor, book chapters and reviews.

Study Selection

Two independent reviewers (EA and CK) performed the literature search and scanned the titles, abstracts, and identifiers of the studies. Studies meeting the inclusion criterias were identified and evaluated as full texts. Any disagreements were resolved through consultation with a third reviewer (UŞ). Figure 1 illustrates the flow diagram of the literature search process.

Data Extraction

The details of the studies, participants' characteristics, and the results were extracted from published data. Data were extracted from the graphs using WebPlotDigitizer 4.6 (California, USA, 2022) (Drevon et al., 2017) when the articles did not provide data and the authors did not give an answer to any communication requests.

Risk of Bias Assessment

Two reviewers (EA and UŞ) used Version 2 of the Cochrane Risk of Bias Tool for randomized trials (ROB 2) (Sterne et al., 2019) to assess the risk of bias, focusing on five domains: the randomization process, deviations from intended interventions, missing outcome data, measurement of the outcome, and selection of reported results. An independent researcher was consulted in the case of any disagreement. The overall assessment consisted of three ratings: high risk of bias, some concerns, and low risk of bias. The risk of bias summary and risk of bias graph are shown in Figure 2.

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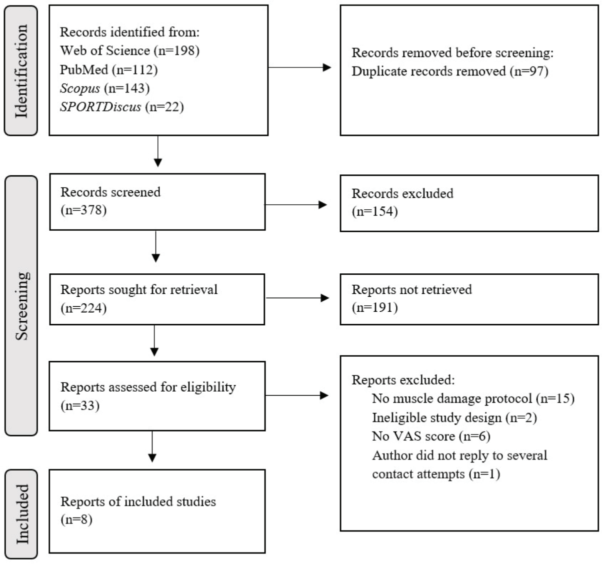

Figure 1. Flow diagram of literature search.

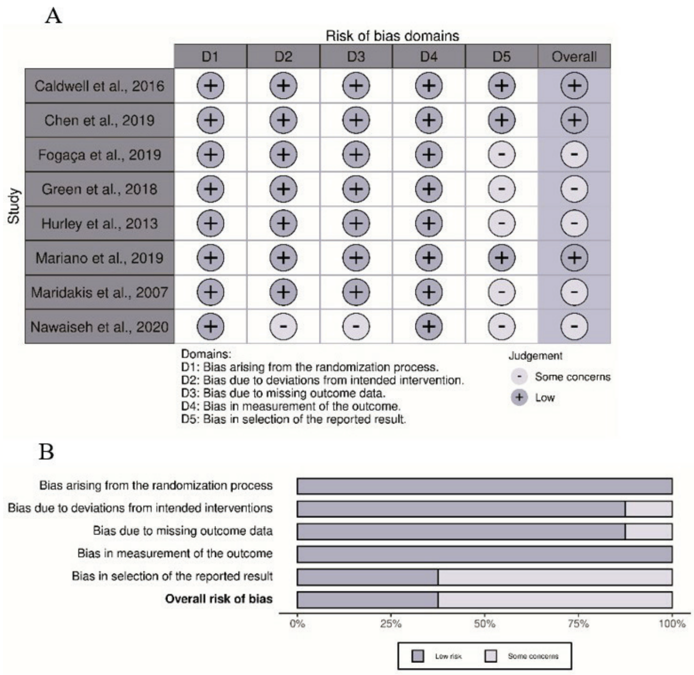

Figure 2. Risk of bias assessment of the included studies: (A) risk of bias summary; (B) risk of bias graph.

Statistical Methods

The Comprehensive Meta-Analysis free trial software (CMA- Version 2 Professional, Biostat Inc., Englewood, USA) was used to conduct all statistical analyses. In the analysis of continuous variables, the standardized mean difference (SMD) and the 95% confidence interval (CI) were computed. Heterogeneity was evaluated using the Chi-square test and the I^2 test. The fixed effects model was used if statistical heterogeneity was not observed ($p>0.05$ and $I^2 <50\%$), while the random effects model was utilized when statistical heterogeneity was identified ($p<0.05$ and $I^2 \geq 50\%$).

Results

General Characteristics of the Included Studies

Out of the 378 initially identified studies, a total of eight randomized controlled trials were incorporated into this meta-analysis. Six of the studies had a crossover design, while two studies used a parallel design. Five trials were conducted in the USA (Al-Nawaiseh et al., 2022; Caldwell et al., 2017; Green et al., 2018; Hurley et al., 2013; Maridakis et al., 2007), 2 in Brazil (Fogaça et al., 2020; Santos-Mariano et al., 2019), and 1 in Taiwan (Chen et al., 2019). All studies were written in English. The subjects consisted of 81 males (70%) and 34 females (30%). Participant ages ranged from 18 to 52 years, with body mass indexes between 20.9 and 27.9. Three studies (Fogaça et al., 2020; Green et al., 2018; Hurley et al., 2013) administered caffeine before muscle damage, while 5 studies (Al-Nawaiseh et al., 2022; Caldwell et al., 2017; Chen et al., 2019; Maridakis et al., 2007; Santos-Mariano et al., 2019) administered caffeine after muscle damage. Caffeine doses varied among studies, with 1 study (Caldwell et al., 2017) using 3 mg/kg, 4 studies (Al-Nawaiseh et al., 2022; Hurley et al., 2013; Maridakis et al., 2007; Santos-Mariano et al., 2019) using 5 mg/kg, and 3 studies (Caldwell et al., 2017; Chen et al., 2019; Green et al.,

Table 1. Characteristics of the included studies

Reference (year)	Subjects info (Training status, sample size, gender, (mean ± SD age)	Study design	Method inducing DOMS	Caffeine dosage (mg. kg−1)	Timing of caffeine ingestion	Soreness data time point	Results
Maridakis et al. (2007)	College-aged 9 females (21,3±1,6)	Double-blind, crossover	Electrically stimulated eccentric exercise of the quadriceps	5 (capsules)	24 and 48 hours following EIMD	24 and 48 hours following EIMD	Caffeine could produce a large reduction in pain resulting
Hurley et al. (2013)	Resistance-trained athletes, 9 males (20±1)	Double-blind, crossover	Four sets of 10 biceps curls followed by a fifth set in which subjects completed as many repetitions as possible	5 (capsules)	60 minutes before completing 4 sets of 10 biceps curls	Before exercise, and 24, 48, 72, 96, and 120 hours after exercise	A significant difference on palpation values with caffeine ingestion on day 2
Caldwell et al. (2016)	Cyclist, 25 Male (53±10 years) 5 female (46±11 years)	Double-blind placebo-controlled	Endurance cycle ride (164-kilometer)	3 (caffeine pills)	Immediately after the ride and next 4 mornings and 3 afternoons	24, 48, and 72 hours following bicycle ride	The caffeine group tended to have lower overall ratings of perceived soreness
Green et al. (2018)	Physically active individuals, 8 male, 8 female, (24,3±4,3)	Double-blind, crossover	Ten sets of 10 eccentric isotonic quadriceps contractions of 3-second duration each on a seated leg extension machine	6 (capsules)	30 minutes before eccentric quadriceps contractions	Immediately before, immediately after, and 24 hours after EIMD	Caffeine or placebo treatments possessed no differences
Chen et al. (2019)	Elite college athletes,10 male (21,1±2,1), 10 female (20,4±1,2)	Double-blind randomized	30-minutes downhill running at a declination of 15% and 70% VO_{2max}	6 (capsules)	24 and 48 hours following EIMD	24, and 48 hours following EIMD	Acute caffeine supplementation is able to attenuate DOMS
Fogaça et al. (2019)	CrossFit athletes, 9 male (28±2)	Double-blind, crossover	CrossFit workout	6 (capsules)	60 minutes before a CrossFit workout	pre, post and 24 hours after the workout	Acute caffeine supplementation of was not able to alter DOMS
Mariano et al. (2019)	Jumper and sprinter athletes, 11 male (18,7±2,7)	Double-blind, crossover	A half-squat exercise (4 x 12 repetitions at 70% of 1 *Repetition Maximum*)	5 (capsules)	24, 48, and 72 hours after	24, 48, and 72 hours after EIMD	Caffeine had no influence on DOMS
Nawaiseh et al. (2020)	Runners, 9 male, 2 female, (24,5±6,3)	Double-blind, crossover	30-minutes downhill run on a treadmill set at -10% grade (70% VO_{2max})	5 (capsules)	60 minutes before the 5 km running	Immediately, 24, and 48 hours, following downhill running	Caffeine is not effective at reducing muscle soreness

DOMS= Delayed onset muscle soreness; EIMD= Exercise-induced muscle damage; SD= Standard deviation; $mg.kg^{-1}$= $milligram/kilogram^{-1}$

2018) using 6 mg/kg. Four studies (Green et al., 2018; Hurley et al., 2013; Maridakis et al., 2007; Santos-Mariano et al., 2019) induced muscle damage through eccentric exercise, while the other 4 studies (Al-Nawaiseh et al., 2022; Caldwell et al., 2017; Chen et al., 2019; Fogaça et al., 2020) used aerobic exercise (Table 1).

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Risk of Bias

All selected studies demonstrated a low risk of bias during the randomization process and reporting of outcome measurements. One study (Al-Nawaiseh et al., 2022) raised concerns about deviations from intended interventions and the presence of missing outcome data. Five studies (Al-Nawaiseh et al., 2022; Fogaça et al., 2020; Green et al., 2018; Hurley et al., 2013; Maridakis et al., 2007) presented some concerns regarding the selection of reported results (Figure 2).

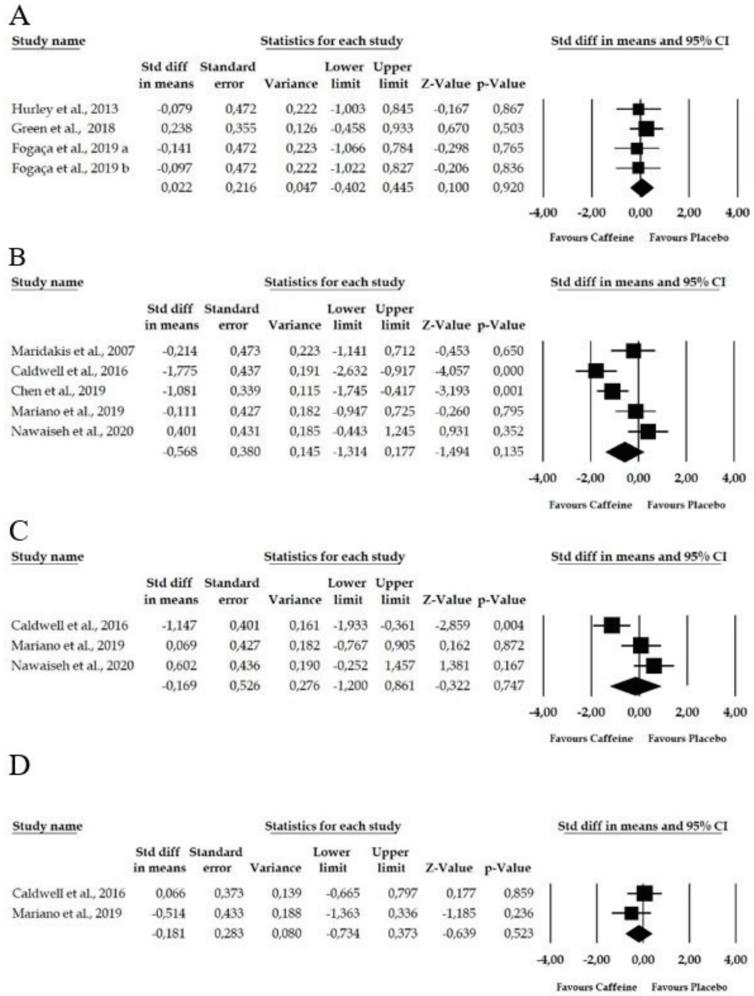

Figure 3. Forest plot for comparison of VAS at 24, 48 and 72 hours between caffeine supplementation and placebo: (A) VAS at 24 hour post-damage in caffeine ingestion before damage (a.biceps femoris muscle pain score, b. quadriceps femoris muscle pain score); VAS at (B) 24, (C) 48, and (D) 72 hours post-damage after caffeine ingestion.

Caffeine Effect on VAS at 24 hours after pre-damage caffeine intake

Effects of caffeine ingestion before muscle damage on DOMS-related pain after 24 hours later were evaluated by 3 studies (Fogaça et al., 2020; Green et al., 2018; Hurley et al., 2013). As Fogoça et al.(Fogaça et al., 2020) evaluated the pain score of the quadriceps and biceps femoris muscles individually, and the scores of both muscle groups were included in the analysis as separate values. No significant differences were found in the mean VAS scores for muscle soreness between the caffeine and placebo groups at 24 hours following exercise. (SMD=0,22, 95% CI -0,40, 0,44; p=0.920) (Figure 3-A). The analysis revealed a low level of heterogeneity across the studies. (Cochran's Q: 0,598, df (Q):3, p=0,897; I^2:0%).

Caffeine Effect on VAS at 24 hours after post-damage caffeine intake

Five studies examined the impact of caffeine consumption on pain associated with DOMS at 24 hours following muscle damage (Al-Nawaiseh et al., 2022; Caldwell et al., 2017; Chen et al., 2019; Maridakis et al., 2007; Santos-Mariano et al., 2019). Caldwell et al. (Caldwell et al., 2017) administered caffeine immediately after damage and at 24 hours, while other studies administered caffeine at 24 hours (Al-Nawaiseh et al., 2022; Chen et al., 2019; Maridakis et al., 2007; Santos-Mariano et al., 2019). No significant difference was found in pain scores between the caffeine group and the placebo group. The analysis revealed no significant difference between the caffeine and placebo groups in terms of pain scores (SMD=-0,568, 95% CI -1,31, 0,17; p=0.135) (Figure 3-B). Statistical heterogeneity was detected between the studies (Cochran's Q:16,596, df (Q):4, p=0,002; I^2:75,89%). Upon performing a subgroup analysis to determine the source of heterogeneity, the results suggested that the caffeine dose and study design could explain the heterogeneity, while exercise type (aerobic or resistance) could not.

Caffeine Effect on VAS at 48 hours after post-damage caffeine intake

The impact of caffeine consumption on VAS score 48 hours after muscle damage was investigated by three studies (Al-Nawaiseh et al., 2022; Caldwell et al., 2017; Santos-Mariano et al., 2019). There was no statistically significant difference between caffeine and plasebo consumption on pain score at 48 hours after muscle damage (SMD=-0.169, 95% CI -1,20, 0,86; p=0,747) (Figure 3-C). A high heterogeneity was seen across studies (Cochran's Q:9,353, df (Q):2, p=0,009; I^2:78,61%) (p=0,009, I^2=78,61).

Caffeine Effect on VAS at 72 hours after post-damage caffeine intake

Two studies investigated the impact of caffeine consumption on pain 72 hours following muscle damage. No improvement in VAS scores was identified after the ingestion of caffeine (SMD=-0,181, 95% CI -0,73, 0,37; p=0,523) (Figure 3-D). A low level of heterogeneity was observed between the studies (Cochran's Q:1,029, df (Q):1, p=0,310; I^2:2,78%).

Subgroup Analysis

A subgroup analysis was carried out to determine if there was evidence for the impact of different caffeine doses on pain scores following exercise-induced muscle damage. A subgroup analysis of (Al-Nawaiseh et al., 2022; Chen et al., 2019; Maridakis et al., 2007; Santos-Mariano et al., 2019) three studies evaluating the effect of 5-6 mg/kg caffeine dose on muscle damage was performed (SMD=-0,287, 95% CI -0,95, 0.37; p=0,398) and it was observed that 5-6 mg/kg caffeine had no significant effect on the pain score compared to placebo (Figure 4-A1). In the analysis of a study (Caldwell et al., 2017) evaluating the effect of 3 mg/kg caffeine (SMD=-1,775, 95% CI -2,63, 0,97; p<0,00) (Figure 4-A2), a substantial effect of 3 mg/kg caffeine on pain score was found compared to placebo.

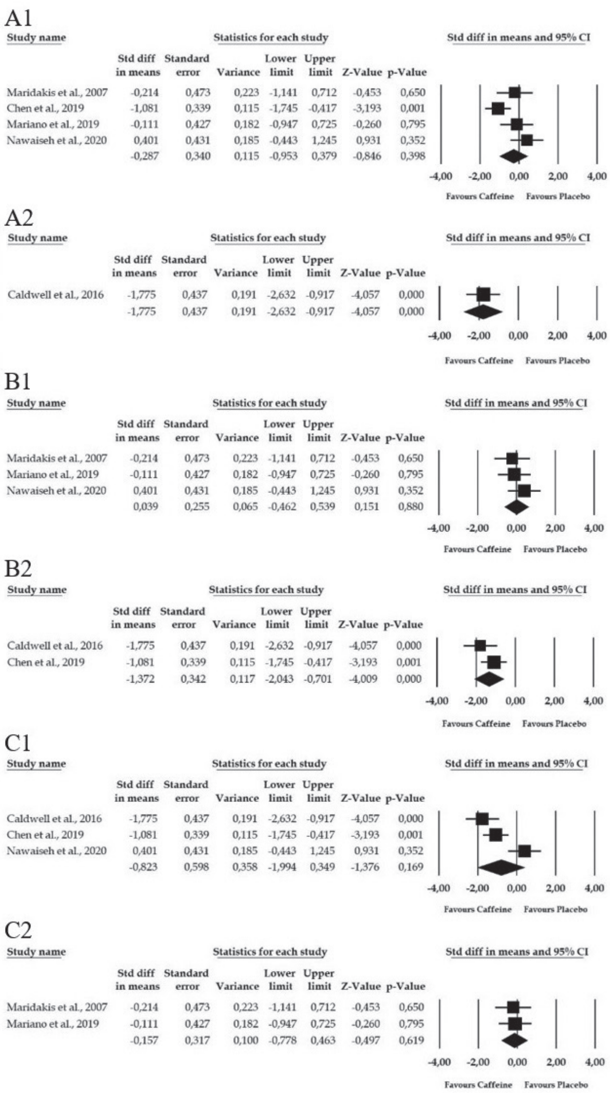

Figure 4. Subgroup analysis of VAS at 24 hours in groups ingested caffeine and placebo after muscle damage: (A1) 5-6 mg/kg caffeine; (A2) 3 mg/kg caffeine; (B1) crossover design; (B2) parallel design; (C1) aerobic exercise; (C2) resistance exercise.

A subgroup analysis of five studies was performed to examine the relationship between study design (crossover-parallel) and pain score during caffeine ingestion. For three crossover studies (Al-Nawaiseh et al., 2022; Maridakis et al., 2007; Santos-Mariano et al., 2019) compared to placebo, caffeine did not have a significant effect on pain (SMD=0,039, 95%

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CI -0,46, 0,53; p=0,880) (Figure 4-B1). In the analysis of two studies (Caldwell et al., 2017; Chen et al., 2019) evaluating the effect of caffeine with a parallel design (SMD=-1,372, 95% CI -2,04, -0,70; p<0,00) (Figure 4-B2), a significant effect of caffeine on pain score was observed compared to placebo.

Three studies (Al-Nawaiseh et al., 2022; Caldwell et al., 2017; Chen et al., 2019) were included in the subgroup analysis for the effect of caffeine use 24 hours after aerobic exercise-related muscle damage. The combined SMD of VAS score for the subgroup of patients with DOMS was -0,823 (95% CI -1,99, 0,34; p=0,169), indicated no significant decrease in VAS score in the caffeine consomption grup (Figure 4-C1). Two studies (Maridakis et al., 2007; Santos-Mariano et al., 2019) evaluating VAS scores of caffeine use 24 hours after resistance exercise-induced muscle damage were included in the subgroup analysis. Compared with placebo, the caffeine group did not show any significant improvement in pain (SMD=-0,157, 95% CI -0,77, 0,46; p=0,619) (Figure 4-C2).

Discussion

This meta-analysis investigated the influence of caffeine supplementation on pain caused by exercise-induced muscle damage. The results of this study show that caffeine supplementation, administered either before or after muscle damage, did not significantly influence the DOMS pain score compared to the control groups.

Caffeine is the most used ergogenic supplement among athletes, with a 75% usage rate before and during the competition (Del Coso et al., 2011). Caffeine increases cellular ion release by stimulating adrenaline secretion (Graham, 2001; Sökmen et al., 2008). When used after exercise, it increases the rate of new glycogen synthesis and glycogen accumulation (Pedersen et al., 2008). In addition, the elevation in heart rate and blood pressure, as well as the extension of the QTc interval resulting from caffeine intake after exercise suggest that the sympathetic recovery period is prolonged. It is important because it can disrupt the stability of autonomic function, especially after exercise termination (Bunsawat et al., 2015). It seems that caffeine use before or after muscle damage has quite different effects on muscle metabolism.

Because of various effects of caffeine on muscle metabolism, pre-exercise ingestion may influence damage formation, while post-exercise use may impact muscle recovery. In the pioneering study by Muljadi et al. (2021) the analysis included studies that assessed the effects of caffeine use on pain before, after, or both before and after exercise-induced damage. Unlike this study, in order to more clearly evaluate the effect of pre- or post-exercise caffeine use on pain, pre- or post-exercise caffeine ingestion was analyzed separately in this study. When the risk of bias assessment was made in the included RCTs, low bias was observed in 3 studies, while some concerns were observed in 5 studies.

First, randomize controlled studies evaluating caffeine use before exercise damage were analyzed to see the effect of pre-injury use on pain. Of the three studies in the literature examining the effect of caffeine use on DOMS-induced pain compared to placebo before muscle damage, Hurley et al. (2013) showed that caffeine was more effective, while Green et al. (2018) and Fogaça et al. (2020) found no difference at 24 hours later. Hurley et al. (2013) indicated that using caffeine in the days following intense resistance training could alleviate pain and facilitate an increase in the frequency of training sessions over time. In contrast, Green et al. (2018) and Fogaça et al. (2020) found that pre-injury caffeine use did not cause a significant reduction in perceived pain at 24 hours compared to placebo. In Muljadi et al. (2021) meta-analysis study, when 7 studies that evaluating the effect of caffeine before, after, or both before and after muscle damage were analyzed together, no significant difference was found in the change in pain score compared to placebo. Similarly, in this meta-analysis study, it was observed that consuming 5-6 mg/kg of caffeine only prior to the muscle damage did not have a significant impact on pain 24 hours later.

Although caffeine use increases the firing rate of muscles by increasing the release of dopamine and glutamate (Kalmar, 2005), according to the available data of this study, the consumption of 5-6 mg/kg of caffeine prior to muscle damage does not influence muscle pain. In order to reveal the effects of caffeine before muscle damage more clearly, studies involving more participants and evaluating different doses are required.

It has been stated that when caffeine is used after exercise, an increase in muscle glucose level is observed (Bunsawat et al., 2015), while it may also prolonged sympathetic recovery time (Pedersen et al., 2008). Five studies exist within the literature just looking at the effects of caffeine and placebo use on DOMS pain after exercise damage. While Chen (2019) and Caldwell (2017) report a more significant decrease in pain scores than placebo with caffeine ingestion, other studies did not find any advantage of caffeine over placebo. Of these studies, only Caldwell et al. (2017) used caffeine (3 mg/kg) both 4 days after the damage and immediately after muscle damage and reported a positive effect of caffeine on pain Analysis of the results from these studies revealed that caffeine consumption does not have a significant effect on exercise-related muscle pain at 24, 48, and 72 hours following muscle damage. When Muljadi et al. (2021) analyzed studies involving caffeine use before, after, or both before and after exercise, they demonstrated that caffeine was ineffective in alleviating DOMS pain at 24 and 72 hours, similar to this study. Differently, they found that caffeine supplements were effective in reducing DOMS pain 48 hours after exercise (Muljadi et al., 2021). In addition, Muljadi et al.'s (2021) meta-analysis study showed that caffeine use during exercise had no effect on Creatine kinase (CK) values are an indicator of muscle damage. Most of the studies examined in the analysis applied caffeine doses of 5-6 mg/kg. The hypoalgesic effects of caffeine may become evident after more rigorous exercise or with varying dosages. Spriet (2014) stated that low and very low doses of caffeine taken at the end of long-term exercise had an ergogenic effect in athletes and may be associated with lower side effects. Considering the studies of Caldwell et al.(2017) and Spriet (2014) together, low-dose caffeine use immediately after muscle damage and in the following days may have an affect on DOMS pain and perhaps muscle damage. Using a low dose of caffeine, such as 3 mg/kg, may help maintain muscle glucose levels without negatively impacting the sympathetic recovery process. To confirm this prediction, studies examining the effects of caffeine immediately following muscle damage and in the subsequent days are needed.

To identify the source of heterogeneity, subgroup analyses were performed with a focus on the 24-hour VAS as the primary outcome. Subgroup analysis was not conducted for the 48-hour mark due to insufficient studies for inclusion. In conclusion, while caffeine dose and study design could explain the heterogeneity, exercise type (aerobic or resistance) could not account for it.

In the subgroup analysis, 5-6 mg/kg caffeine dose had no effect on DOMS pain, while 3mg/kg caffeine reduced the pain score. However, there is only one study using 3mg/kg caffeine, so it is not possible to clearly demonstrate the effect of low dose caffeine. In the literature, various doses of caffeine (5, 6, and 10 mg/kg) are employed in studies investigating its impact on muscle pain caused by exercise (Al-Nawaiseh et al., 2022; Chen et al., 2019; Maridakis et al., 2007; Motl et al., 2006; Santos-Mariano et al., 2019). Low-dose caffeine use (3 mg/kg) has also been reported to reduce muscle pain (Caldwell et al., 2017; Ganio et al., 2011). According to Spriet (2014) , low-dose caffeine use in athletes may have an ergogenic effect and is also associated with fewer side effects. Although this view of Spriet's (2014) supports the Caldwell study (2017), which used 3 mg/kg caffeine in its study, but more studies examining these effects of low-dose caffeine are needed.

The subgroup analysis according to study design revealed no significant difference in VAS scores between caffeine and placebo in crossover studies. In contrast, parallel studies found that caffeine had a significant effect on VAS scores compared to placebo. Consistent with the present study, Muljadi et al. (2021) observed a significant impact of caffeine on VAS scores in parallel-design studies, while crossover-design randomized controlled studies showed no significant effect. They also stated that crossover studies may not be very appropriate, because of the exercise damage to the muscle may last for a long time and may affect the formation of exercise damage again (Muljadi et al., 2021). Additionally, complete blinding can be difficult when using supplements and placebo in crossover studies, and the washout time of caffeine can cause problems.

The subgroup analysis assessing aerobic and resistance exercises indicated that the pain scores of the two groups were not statistically significantly different. In contrast, Muljadi et al. (2021) reported that caffeine intake 24 hours after resistance exercise reduced VAS. However, unlike in this analysis, they analyzed studies that used caffeine before or after exercise together. Due to the few studies available and the diversity in doses and exercise damage models, evaluating the analyses becomes challenging. Additional studies are required to explore the connection between caffeine and DOMS.

This is the first study to examine the impact of caffeine use on pain scores before or after DOMS using randomized controlled trials. Additionally, this study presents some limitations. The initial limitation is the relatively low number of studies included, reflecting the limited scope of available literature. As most studies included in the meta-analysis lacked reports of these values, there was not enough data to assess the muscle damage markers. Moderate to significant heterogeneity existed for several outcomes. The heterogeneity was attributed to the limited number of studies as well as the presence of studies with different exercise models and athlete groups. When assessing heterogeneity, most of the subgroup analyzes had to be conducted on a small number of studies. In addition, this meta-analysis included only English-language articles, and no registration was performed.

Conclusion

According to the current meta-analysis, a caffeine dosage of 5-6 mg/kg administered before or after muscle damage does not effectively reduce muscle pain associated with DOMS. It is possible that caffeine could have a hypoalgesic effect following a more strenuous exercise session or when administered at doses different from 5-6 mg/kg. Future studies may consider evaluating the effects of a 3 mg/kg caffeine dose on DOMS pain and potential side effects. Furthermore, to more clearly understand caffeine's analgesic effect, research evaluating various doses and timing of caffeine intake before and after exercise-induced damage is required.

Conflict of interest

The authors declare that there is no conflict of interest.

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ORIGINAL SCIENTIFIC PAPER

Relationship between the Horizontal Force-Velocity Profile and Performance Variables obtained in Sprinting, Slalom Test, and Kicking in Amateur Soccer Players

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Abstract

This study evaluated the mechanical determinants of 30 m sprint performance in 110 amateur soccer players and identified variables of sprint, slalom, and kick tests. Associations were identified using Pearson's correlation coefficient. A p-value of 0.0007 was considered statistically significant for all analyses after performing Bonferroni correction adjustment. Relative peak running power (P_{max}) was significantly correlated ($p<0.0007$, $r=-0.875$ to -0.984) with sprint split times across all distances (5–30 m). Relative theoretical maximum horizontal force (F_0) significantly correlated with acceleration performance (0-15 m, $p<0.0007$, $r=-0.756$ to -0.951). Average ratio of forces for the first 10-m (RF_10m) was significantly correlated ($p<0.0007$, $r=-0.909$ to -0.965) with sprint split times across 20–30 m and gap time at 10-20 m and 20-30 m. Maximal value of ratio of force (RF_{max}) was significantly correlated ($p<0.0007$, $r=-0.718$ to -0.959) with sprint split times across 5–25 m. Theoretical maximum velocity (V_0) was significantly correlated , ($p<0.0007$, $r=-0.540$ to -0.684) with sprint times across 20–30 m, and gap time 10-20 m and 20-30 m ($p<0.0007$, $r=-0.880$ to -0.915). These results indicate emphasis should be placed on training protocols that improve relative peak running power (P_{max}), particularly in time-constrained environments such as team sports, focusing on maximal force production or maximal running velocity ability. Furthermore, attention should be paid to the technical component of the received force in the horizontal direction to the monitor training adjustments and further individualize training interventions.

Keywords: *horizontal F-v parameters, changes of direction, maximal kick ball velocity*

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Introduction

The ability to perform soccer-related tasks at high velocities is believed to be a key factor for reaching success in soccer (Faude et al., 2012). Sprinting is the most frequent action in goal situations in the first German national league, both for the scoring and assisting player (Faude et al., 2012). A high acceleration and a fast maximal sprint speed might allow players to overtake opponents and win balls (Mendez-Villanueva et

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al., 2012). A soccer player changes direction every 2-4 seconds (Verheijen, 1997) and makes 1,200-1,400 changes of direction during a game (Bangsbo, 1992). Kicking is one of the most frequently used skills in soccer, and the most fundamental for soccer performance (Bacvarevic et al., 2012). Ball speed could be particularly important while kicking towards the goal because the chances of scoring increase with an increased ball speed (assuming that the kick is accurate) because the goalkeeper has less time to react (Dörge et al., 2002; Markovic et al., 2006).

Recently was introduced a field-based method of assessing an athlete's sprint ability and the mechanical determinants associated with sprint performance (horizontal power, force, and velocity variables) (Samozino et al., 2016). Mechanical properties of an individual's force-velocity sprinting profile (F-v) were derived from equations that used split times, anthropometric, and spatiotemporal data of the athlete (Samozino et al., 2016). This approach was found to be highly valid (p<0.001, r=0.826 - 0.978) when compared with direct measurement methods of ground reaction forces (GRF) from in-ground force plates (Cross et al., 2017; Samozino et al., 2016). This and other laboratory-based methods of analysing sprinting have shown an athlete's ability to produce high levels of horizontal power during a sprint performance to have a very large to near perfect association (p=<0.01, r=0.850 - 0.932) with their sprint performance (Cross et al., 2015; Morin et al., 2012). However, athletes with differing F-v profiles could potentially produce similar peak horizontal running power (P_{max}) values, which could limit insight to an athletes true F-v profile and where their strength and weaknesses lie (Cross et al., 2017; Morin & Samozino, 2016). The insight into an athletes F-v sprint profile has the potential to influence individualized training interventions and the monitoring of training adaptations (Morin & Samozino, 2016; Samozino et al., 2016). Previous research examining the sprint mechanics of athletes have also shown the determinants of better acceleration (0–20-m) compared with longer distance sprint performance could potentially differ (Buchheit et al., 2014; Cross et al., 2015; Morin et al., 2012). For example, better longer distance sprint performance (≥40 m) and maximal running speeds, has been shown to have a very large association with a more velocity dominant F-v profile (greater maximum velocity and theoretical maximum velocity extrapolated to when force is 0) (Buchheit et al., 2014; Morin et al., 2012). Whereas a more force dominant F-v profile (greater maximum horizontal force and greater theoretical maximum horizontal force extrapolated to when velocity is 0) was found to have a very large association with better acceleration performance in sprints of less than 20 m in elite rugby (Cross et al., 2015) and highly trained youth soccer athletes (Buchheit et al., 2014).

Considering the strong link between game performance and sprint ability in soccer and other team sports, a simple conclusion would be to focus training to high-speed sprinting. Research in sprinters and team sport athletes has identified associations between sprint performance and various F-v characteristics (Morin et al., 2012). Researchers have been found that acceleration, speed, and agility be independent, different qualities that generate a restricted transfer to each other (Jovanovic et al., 2011). But recent study (Falces-Prieto et al., 2022) found moderate to large relationships between short sprint (10-m) performance and change of direction (COD) performance at different angles (180° or 90°). Zhang et al. (2022) find that sprinting F-v profiles parameters were weakly to moderately correlated with 505-test performance (p<0.05-0.001, r=-0.47 to -0.38) in female and male soccer players. Very large correlation between horizontal mechanical parameters (F_0 and P_{max}) and 505-test performance (p<0.001, r=-0,79 to –0,83) in tennis, soccer and basketball player (Baena-Raya et al., 2021). No research was found on associations between maximal kick ball velocity and F-v characteristics, but De Witt & Hinrichs (2012) find significantly correlated segmental foot velocity with ball velocity during an instep soccer kick. Therefore, the purpose of this study was to evaluate the mechanical determinants across 30 m sprint performance in amateur soccer players, using modelled inverse dynamics techniques (Samozino et al., 2016). A secondary purpose was to identify the existence of relationships between horizontal F-v variables of 30 m sprint and performance variables 30 m sprint, slalom, and soccer kick.

Methods

Experimental Approach to the Problem

A cross-sectional study design was used to determine the mechanical determinants of sprint running and the relationship with performance variables in sprinting, slalom tests, and kicking in amateur soccer player. All athletes were tested during the competitive season, minimum 72 hours after a match day or intensive training.

Subjects

One hundred ten amateur soccer players (age=22.6±3.7 years; height=1.81±0.07 m; mass=78.4±7.6 kg) were recruited for this study. The athletes were recruited from 7 clubs Croatian Third Football League. The research was aligned with the Helsinki declaration, and the Scientific and Ethical Committee of the Faculty of Kinesiology, University of Zagreb, approved the experimental protocol. All athletes provided written informed consent for the study after explanation of the purpose, benefits, and potential risks involved.

Procedures

All athletes performed a 15 min warm-up consisting of 6 run intervals of 100 m at a speed≤10 km/h, mobility exercises, athletic running exercises, proprioception exercises and dynamic stretching exercises were performed at a distance of 12 m. Exercises were performed in one direction, and running on the way back at a speed≤10 km/h. The last exercise in warm-up was a maximum sprint 30 m (3 repetitions with 1 min rest). With a 6 minute rest after the warm-up, the subjects were randomly divided into 3 test stations (sprint, slalom tests, and kick test). All tests are performed on outdoor soccer field with natural grass.

Sprint test was performed 2 maximal efforts 30 m sprint, with 3 min rest, where split times (at 5, 10, 15, 20, 25 and 30 m) were assessed by recording each sprint using an iPhone 8 and MySprint app (Romero-Franco et al., 2017). Slalom test was performed 2 maximal efforts on a 11 m long track, with 3 min rest (Sporis et al., 2010). Time is measured by photocells of the system (Witty Gate, Microgate; USA). Soccer kick was performed 3 maximal efforts, with 1 min rest (Markovic et al., 2006). Athletes kicks a stationary ball (Adidas, UCL PRO, size 5) of standard size and standard inflation approved by the International Federation of Football Associations (FIFA). Athletes himself determines the length of the run, the angle of

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the shot and the part of the foot with which hits the ball. Ball speed was measured with a radar (Stalker Pro, Applied Concepts Inc., Richardson, Texas, USA).

Statistical Analyses

Data are presented as mean ± standard deviations (SD). Normal distribution for all variables was confirmed by the Shapiro–Wilk test (p>0.05). Pearson's correlation coefficient was used to assess the strength of the relationship between mechanical sprint variables and sprint split times at 5, 10, 15, 20, 25, 30 m and gap times 10-20 and 20-30m, time at slalom test and ball speed at soccer kick. Evaluation of correlation coefficients were classified as: small=0.1-0.29, moderate=0.30-0.49, large=0.50-0.69, very large=0.70-0.89, nearly perfect=0.90-0.99, perfect=1.0 (Hopkins et al., 2009). Bonferroni correction was set up at p<0.0007.

Results

Descriptive statistics for all performance measures and calculated variables of the 30 m sprint are presented in Table 1. Relative horizontal peak running power (P_{max}) had a negative relationship with all split times across the 30 m, particularly at 10, 15 and 20 m (Table 2). Relative theoretical maximum horizontal force production at 0 velocity (F_0), showed very large to near perfect inverse relationships across split times at 5, 10 and 15 m (range, r=-0.756 to -0.951). Average ratio of forces for the first 10-m (RF_10m) showed near perfect inverse relationships with split times at 20, 25 and 30 m (range, r=-0.909

Table 1. Descriptive Statistics of 30-m Sprint, Slalom Test and Soccer Kick

Test	Measurement	Mean ± SD
30-m Sprint Performance Measures	5 m time (s)	1,32 ± 0,07
	10 m time (s)	2,06 ± 0,08
	15 m time (s)	2,70 ± 0,09
	20 m time (s)	3,33 ± 0,11
	25 m time (s)	3,92 ± 0,13
	30 m time (s)	4,50 ± 0,16
	10-20 m gap time (s)	1,27 ± 0,05
	20-30 m gap time (s)	1,17 ± 0,05
30-m Sprint Calculated Variables	P_{max} (W/Kg)	18,12 ± 1,88
	F_0 (N/Kg)	8,08 ± 0,81
	RF_10m (%)	32,57 ± 1,24
	RF_{max} (%)	52,99 ± 2,81
	D_{RF} (%)	-8,27 ± 1,08
	V_0 (m/s)	8,98 ± 0,54
	V_{max} (m/s)	8,67 ± 0,48
Slalom Test	ST time (s)	7,28 ± 0,28
Soccer Kick	SK ball speed (km/h)	110,99 ± 5,53

Note. P_{max}: relative peak power; F_0: relative theoretical maximum force at 0 velocity; RF_10m: average ratio of forces for the first 10 m; RF_{max}: maximal value of RF; D_{RF}: rate of decrease in RF with increasing speed during sprint acceleration; V_0: theoretical maximum velocity at 0 force; V_{max}: maximum velocity.

Table 2. Pearson's Correlation Coefficients between the Mechanical Determinants During a 30-m Sprint with Sprint and Slalom Times and Ball Speed at Soccer Kick

	P_{max} (W/Kg)	F_0 (N/Kg)	RF_10m (%)	RF_{max} (%)	D_{RF} (%)	V_0 (km/h)	V_{max} (km/h)
5 m (s)	-0,878*	-0,951*	-0,405*	-0,953*	0,742*	0,130	0,095
10 m (s)	-0,984*	-0,880*	-0,680*	-0,959*	0,530*	-0,172	-0,210
15 m (s)	-0,981*	-0,756*	-0,825*	-0,882*	0,327*	-0,384*	-0,421*
20 m (s)	-0,945*	-0,632*	-0,909*	-0,788*	0,157	-0,540*	-0,573*
25 m (s)	-0,908*	-0,547*	-0,947*	-0,718*	0,051	-0,626*	-0,657*
30 m (s)	-0,875*	-0,482*	-0,965*	-0,663*	-0,024	-0,684*	-0,714*
10-20 m (s)	-0,569*	-0,052	-0,941*	-0,271	-0,447*	-0,902*	-0,915*
20-30 m (s)	-0,600*	-0,100	-0,936*	-0,306	-0,395*	-0,880*	-0,898*
ST (s)	-0,248	-0,129	-0,291	-0,186	-0,023	-0,196	-0,196
SK (km/h)	0,069	-0,170	0,305	-0,099	0,347*	0,418*	0,426*

Note. P_{max}: relative peak power; F_0: relative theoretical maximum force at 0 velocity; RF_10m: average ratio of forces for the first 10 m; RF_{max}: maximal value of RF; D_{RF}: rate of decrease in RF with increasing speed during sprint acceleration, V_0: theoretical maximum velocity at 0 force; V_{max}: maximum velocity; *p<0.0007.

to -0.965) and with gap time at 10-20 and 20-30 m (range, r=-0.936 to -0.941). Maximal value of ratio of force (RF_{max}) showed near perfect inverse relationships with split times at 5 and 10 m (range, r=-0.953 and -0.959) and very large inverse relationships with split times at 15, 20 and 25 m (range, r=-0.718 and -0.882). Rate of decrease in ratio of force with increasing speed during sprint acceleration (D_{RF}) showed large to very large relationships with split times at 5 and 10 m (r=0.530 and 0.742), and moderate with gap time at 10-20 and 20-30 m (r=-0.395 to -0.447). Theoretical maximal velocity at 0 force (V_0) and maximal velocity (V_{max}) showed large to very large inverse relationships with split times at 20, 25 and 30 m (range, r=-0.540 to -0.714) and very large to near perfect inverse relationships with gap time at 10-20 and 20-30 m (r=-0.880 to -0.915). The correlation between the time in the slalom test and the mechanical parameters of the 30 m sprint is small and statistically insignificant. At soccer kick ball speed had a positive moderate relationship with D_{RF} (r=0.347), V_0 (r=0.418), and V_{max} (r=0.426).

Discussion

This cross-sectional study evaluated the mechanical determinants of a 30 m sprint in amateur soccer players using modelled inverse dynamic methods (Samozino et al., 2016) and second, examined possible relationships between the 30 m sprint F-v variables with performance in sprint, slalom, and soccer kick. Results show that F-v variables would be a strong indicator of sprint split time performance over 30 m and some F-v variables (V_0, V_{max} and D_{RF}) would be an indicator of performance in soccer kick test. However, the association of F-v variables with performance in slalom test was not found.

The results of this study did not show great variation between athletes' sprint times, particularly over the first parts of the sprint (<15 m), with SD ± 0.07–0.09 seconds separating athletes at 5, 10, and 15 m times, suggesting a relatively homogenous population. However, greater relative horizontal forces (F_0) and maximal ratio of forces applied onto the ground (RF_{max}) what objectively represent runners' force application technique (Morin et al., 2011) were associated with athlete's acceleration performance (0-15 m) in our study. Highlighting the importance of armature soccer players to be able to produce, and effectively apply, greater relative F_0 and RF_{max} as a critical quality to better acceleration and on-field success.

In this study, the sprint ability of amateur soccer player over 20 m (3.33±0.11 s) was similar to the sprint performance of first division soccer players (3.38±0.12 s); and first division futsal players (3.36±0.09 s) (Jiménez-Reyes et al., 2019). Likewise, power and force production at the beginning of the sprint in this study was slightly better that in first division soccer and futsal player (Jiménez-Reyes et al., 2019). But application of force at high speeds (V_0 and D_{RF}) was better in in first division player (9.25±0.61 and -7.08±0.82), than in this study (8.98±0.54 and -8.27±1.08). According to the (Haugen et al., 2020) our mechanical parameters and sprint performance values are similar to player in 3rd-5th division. Disagreement in results may influence poor warm-up protocol in study (Jiménez-Reyes et al., 2019), only jogging and lower limb dynamic stretching was included. One must also keep in mind that sprint performance and mechanical properties may vary between conditions due to differences in footwear and surface (Haugen & Buchheit, 2016) as was the case between the two studies mentioned. Furthermore, (Morin et al., 2012) found that the ability to orient the resultant GRF vector effectively (i.e. forward) during the entire acceleration phase (D_{RF}) strongly differed between the fastest and slowest individuals.

The present results confirm earlier findings in which was determined highest correlation between P_{max} and RF_10m whit sprint performance (Haugen et al., 2020). Furthermore, our results confirm earlier findings that shorter the distance considered, the higher relationship between F_0 and RF_{max} and sprint performance, whereas and V_0 become more determinant as both the distance and velocity increases (Haugen et al., 2020). Overall, D_{RF} in our study significant correlation 0.742, 0.530, 0.327 with 5, 10, 15 m time, respectively. Since D_{RF} is combination of maximum velocity and relative acceleration, and therefore has an interdependence on the individual slope of the force-velocity relationship. Typically, as one value moves up (i.e., relative force), the other value will likely move down (i.e., velocity) changing the force-velocity value (Hicks et al., 2023). Because of this D_{RF} is a parameter that should be put in the context with performance at longer sprint distances and gap times. We found a correlation -0,447 and -0,395 with gap time 10-20 and 20-30 m, respectively. Oure results confirm earlier findings that D_{RF} was moderate correlation (-0.41) with 40 m time (Haugen et al., 2020), large (0.683) with 4 s distance (m), very large (0.729 and 0.875) with maximal speed and 100 m speed (ms-1) (Morin et al., 2012). Association the weakest correlations with sprint performance, which may have occurred due to the lower level of athletes in this study. Studies with national-level athletes found stronger correlations (Haugen et al., 2020; Morin et al., 2011, 2012).

Mechanical variables might add valuable information about performance of short sprint acceleration. For instance, two players may have the same 5 or 20 m split time but different F_0 or, what is more, the same F_0 but different mechanical effectiveness values which is determinant in the acceleration phase (Morin & Samozino, 2016). In this example, prescribing a similar training program for these two players with the aim to optimize athlete's acceleration ability might result in suboptimal adaptations for maximal linear velocity, since the specific F-v profile mechanical variables underlying short sprint acceleration would not be addressed. Therefore, assessing the sprint F-v profile might help coaches to describe athlete's acceleration ability and prescribe specific training program to improve the acceleration and linear velocity.

Our study found no correlation between horizontal mechanical parameters and performance in slalom test, which is in contradict with study (Baena-Raya et al., 2021), who find very large corelation between horizontal mechanical parameter (P_{max}, F_0) and performance in 505 COD test in tennis, soccer and basketball player. Conflicting findings can be explained by different COD angles, result in a different level of involvement of basic motor components, namely force or speed, when changing the direction of movement. Sigward et al. (2015) confirms that GRF magnitudes are significantly greater with sharper cuts, also direction requirements of the force are different (i.e. greater posterior and laterally directed force for sharper CODs). Therefore, it seems important to distinguish those tests in which there were numerous changes of direction based on speed (angle≅0° to ≅90°) or force (angle≅135° to ≅180°; (Nygaard Falch et al., 2019). Therefore, it was suggested that COD and linear sprint should be trained independently due to the low to moderate relationships between these abilities (Salaj & Markovic, 2011).

In fact, to the best of our knowledge, this is the first study

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that investigated relationship between horizontal mechanical parameters and maximal soccer kick. A moderate association between V_0, V_{max}, D_{RF} and ball speed suggests that velocity is a stronger determinant of maximal soccer kick than power. Respectively, application force at higher speeds is more determinant ball speed than application force at lower speeds. Which coincides with finding that ball speed of the soccer kick depends on the speed of the foot before impact (Dörge et al., 2002) and lower peak braking forces under the support leg were associated with higher ball velocities (Orloff et al., 2008).

Performance data alone provide a basis for convenient analysis on the field, but sprint mechanical outputs provide deeper insights into individual biomechanical limitations. Future studies should explore the effects of individualized sprint training based on mechanical properties. The current data provides a point of departure for this purpose.

There are several limitations that must be considered when interpreting the results of this study. The current investigation used modelled running mechanics obtained from sprint times and a validated inverse dynamics approach (Samozino et al., 2016) as opposed to directly measuring GRF. This method does not allow for evaluation of inter-limb or inter-step variability; however, the simplicity of the experimental approach along with the method's sensitivity to highlight small mechanical differences between sprinting profiles in a relatively homogenous sample group, highlights its use in many field-based settings. Furthermore, this cross-sectional design precludes establishing causal relationships and these results must be contrasted in future prospective research. Assessing whether optimizing the F-v profiles through specific training programs translates into an improved speed and kick performance (due to the improvement in acceleration capabilities) is warranted. Finally, because the sample population in this study were amateur soccer player, our results may not be generalizable to other athletes.

In summary, ability to accelerate their own mass by producing greater relative forces, over shorter periods of time and at greater velocities were important to the athletes' sprint and soccer maximal kick performance. Further research should examine the impact of individualized, orientation-specific training protocols on the orientation of an athletes' F-v sprinting profile and overall mechanical sprint ability.

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ORIGINAL SCIENTIFIC PAPER

Impact of Three Weekly Sessions of Complex versus French Contrast Training on Physical and Physiological Responses in Field Hockey Players: A Randomized Control Trial

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Abstract

This investigation aimed to shed light on the potential benefits these training methods can offer athletes attempting to improve their abilities in their game on the field. The complex training group (CMT), the French contrast training group (FCT), and the active control group (ACG) comprised 15 male field hockey players (Total 45 field hockey players) with an average age of 19.42±1.18 years. These players were randomly allocated to three equal groups. There were 36 training sessions in each training group over three months, with CMT and FCT training interventions being carried out thrice weekly. Participants in the ACG group went through their daily hockey practice regimen. In physical outcome measures, there were no significant differences in speed across groups (p=0.280), but significant variations were seen with time (p<0.01) and when groups and time were combined (p<0.01). Significant differences were seen for Change of direction (COD) and muscular endurance (ME) between groups (p<0.01) across time (p<0.01) and in the interaction between groups and time (p<0.01). In physiological outcome measures, anaerobic power (AP), vital capacity (VC), and VO2 max showed significant changes between groups (p<0.01) over time (p<0.01) and in the interaction between groups and time (p<0.01). In contrast, resting heart rate (RHR) showed no significant variations between groups (p=0.317), either across time (p=0.662) or in the interaction between groups and time (p=0.052). It concluded that CMT and FCT enhanced hockey players' COD, ME, AP, VC, and VO2 max. The FCT group outperformed the CMT group, proving its usefulness in improving athletic performance.

Keywords: *anaerobic power, complex training, French contrast training, vital capacity, VO2 max*

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Introduction

Hockey is a team sport requiring various equipment, involving unpredictable movement patterns influenced by the dynamic and longer match condition (McGuinness et al., 2017) . During the match, field hockey players engage in high-speed running, quick directional changes, and accelerations, utilizing strategic offensive and defensive maneuvers within confined spaces to optimize performance and secure the competitive success (McGuinness et al., 2020). The field hockey game has seen a substantial increase in the physical demands placed on players over the previous ten years. Particularly challenging on the lumbar spine and lower limbs are the distinctive flexed hip/trunk postures, rapid speed changes, and quick directional shifts characteristic of this exercise (Beddows et al., 2020). For much of the game, players must possess the following physical skills: power, endurance, muscular strength, and dynamic balance (Ramasamy et al., 2022). Any disruption to these activities during play will increase a player's risk of many injuries and reduce their effectiveness (Stokes et al., 2020). Suggestions from previous narrative and systematic reviews and meta-analyses have highlighted the significance of the treatment options by improving physiological and physical outcomes and lowering several injury risk variables in a variety of sports populations (Dolci et al., 2020; Lesinski et al., 2020; Moscatelli et al., 2023; Ramirez-campillo et al., 2021, 2022; Saeterbakken et al., 2022; Thiele et al., 2020; Vasconcelos et al., 2020; Vincent et al., 2022), which includes resistance and plyometric training interventions. In recent times, strength and conditioning coaches and trainers have been increasingly embracing these training methods in order to enhance the athletic performance of their athletes (Ramirez-campillo et al., 2021; Saeterbakken et al., 2022) especially the combination of both in the same training (Oliver et al., 2024). Some earlier studies referred to complex training (CMT) as an alternative term for combining plyometric and resistance training in a single workout session, which was becoming increasingly popular among the experts (Ojeda et al., 2016).

By analyzing fitness testing results, sports scientists and strength and conditioning professionals can better grasp their athletes' present fitness profiles. It is possible to use this information to build a training program that corresponds to each player's requirements, including the requirements of their playing position (Pešič et al., 2024; Turner et al., 2019). A strong aerobic capacity and the ability to undertake repeated high-intensity efforts while simultaneously accurately performing difficult stick and ball skills are two primary performance markers associated with top-level competition (Lombard et al., 2021). As with many individual and team sports, the length of the competition makes aerobic endurance more crucial for the participants, but there are also a lot of sprint and power actions that play a role in hockey competition victory. Due to the influence of stick swing speed and players' ability to change direction, sprint and agility talents are crucial for competitive success in hockey. Consequently, in field hockey training, training regimens that increase an athlete's strength and speed are frequently used in addition to endurance training (Güllich, 2014).

The concept of 'complex training' refers to a training mode that combines one set of strength training with a similar set of plyometric exercises in the same training session and is thought to improve the quality of the plyometric training stimulus. Combining biomechanically comparable workouts is beneficial for boosting force production and dynamic power rate through improved neuromuscular control. High-intensity resistance training prepares the body for plyometrics by affecting neuromuscular, hormonal, metabolic, and psychomotor aspects. This method promotes neural adaptations that enhance physical abilities (Ali et al., 2017). A study by Kanniyan and Syed (2013) emphasizes that the results demonstrated a significant improvement in all evaluated variables compared to the control group for both the CMT and contrast training groups. Throughout a 10-week training session, the CMT group improved more than the contrast training group in several areas, such as speed and muscle endurance, even though the contrast training group also showed notable advantages in resting heart rate (RHR) and cardiorespiratory endurance. CMT's ability to increase the power of lighter exercises is believed to be due to PAP (Robbins, 2005).

CMT refers to varying movement velocity or load between sets or exercises within a session to improve slow and fast force expression. There are four types of CMT: contrast training, ascending training, descending training, and French contrast training (FCT), which involves performing a series of exercises (Cormier et al., 2022)with a combination of both CMT and contrast training (Michael et al., 2022), entails performing a series of exercises in a single session in a specific order. These exercises include things like heavy compound exercises (resistance exercises), lighter exercises (plyometric exercises), light-to-moderate load compound exercises that maximize movement speed (also externally loaded power exercises), and an assisted plyometric exercise (Gould, 2021). The FCT Method is one of the many CMT approaches that have been presented in order to have the most significant possible impact on the post-activation performance enhancement (PAPE) phenomena (Rebelo et al., 2023; Türkarslan & Deliceoğlu, 2024) even though PAP and PAPE are connected (Villalon-gasch et al., 2022), it is possible to consider them to be two distinct phenomena. This is because the processes that cause PAP are distinct from those that produce PAPE. Electrostimulation is the source of PAP, characterized by an increase in the efficiency of contractions due to a more optimal coupling of actin and myosin (Chen et al., 2017).

On the other hand, PAPE is associated with various factors, including but not limited to conditions such as the temperature of the muscle, the amount of water present in the muscle fibres, and the number of motor units that are activated (Blazevich & Babault, 2019). As a result, their effects may manifest at varying periods and degrees of intensity (Zimmermann et al., 2020). Previous research has only conducted a limited number of studies that have studied the impact of CMT on the physical and physiological variables (Kanniyan & Syed, 2013), especially on hockey players (Rathi et al., 2023; Thapa et al., 2023). Some of them explore the influence of FCT on agility (Salam & Sherif, 2020), speed (Türkarslan & Deliceoğlu, 2024), maximal strength and power (Rebelo et al., 2023) and some of the other physical variables (Elbadry et al., 2019; Welch et al., 2019). No experiment has been carried out in the past that has discriminated between the effects of CMT and FCT on physical and physiological characteristics among field hockey players. Hence, the researcher aimed to explore the influence of CMT and FCT on physical and physiological variables among field hockey players and determine which training intervention has highly influenced those variables over 3-months of intervention.

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Methods

Ethical approval

All of the participants in this study were provided with information on the aims and general procedures of the whole research project, and they voluntarily consented to participate in the study by signing a written consent form that the committee authorized. This was done to ensure that the scientific findings obtained from this study were reliable. The study was conducted by the declaration of Helsinki (World Medical Association, 2013) and received approval from the institutional ethics committee at Pondicherry University (Approval No. HEC/PU/2023/05/07-08-2023).

Participants

Fifty male hockey players from Union Christian College in Aluva, India, provided written consent and agreed to participate in this study. One of the inclusion criteria was five years of playing experience in field hockey, and two years of resistance training and plyometric experience were fixed. Players with a history of musculoskeletal injury were omitted from this study according to the exclusion criteria. In this study, five hockey players were removed prior to the initial test due to a history of pre-existing musculoskeletal injury. The researcher utilized the G*Power 3.1.9.7 software Franz Faul developed at the University of Kiel in Germany to determine the appropriate sample size. During the calculation, the following variables were taken into consideration: effect size for within-between interaction in repeated measures ANOVA: three groups, two measurements, and a priori: compute required sample size - given, power, desired power (1-ß error) =0.80, alpha error <0.05, non-sphericity correction =1, effect size (f) of 0.25, the correlation between repeated measures =0.5, and effect size (f) of 0.25. According to the results of the computation of the sample size, a minimum of 42 participants would be necessary in order to attain statistical significance in the context of the study (Chovanec & Gröpel, 2020). Given the possibility of individuals dropping out of the study, a slightly higher sample size of 45 male participants was considered for this study. To assess the power (1-ß error) with 45 participants, post hoc: compute achieved power-given sample size, and effect size was tested using G*Power. The output parameter shows that the power (1-ß error) =0.83, which is increased by 0.03. After the inclusion and exclusion criteria, the selected participant's (n=45) age was 19.47±1.16, height: 1.69±0.07, weight was 64.16±4.98, and body mass index (BMI) was 22.44±1.26. No dropouts were observed after or during the training program.

Study design (Experimental approach to the problem)

A 3x2 randomized controlled trial was conducted over three months to examine the effects of CMT and FCT on selected parameters in field hockey players. The participants were classified into three groups, each comprising fifteen participants. The CMT group carried out the Complex training intervention, while the FCT group carried out the French contrast training intervention. Both intervention groups participated in three sessions per week over 3-months of intervention, and participants received ample recovery between sessions. The active control group (ACG) performed no exercises beyond the regular field hockey training. Demographic data were obtained before the training program and familiarization session started. Participants completed two weeks of familiarization sessions, comprising CMT and FCT activities, and one session for the testing process. One repetition maximum (1 RM) test was conducted at least one week before baseline testing. During familiarization sessions, participants performed squats, box jumps, bench presses, a 1 kg medicine ball overhead wall throw for CMT training and squats, and box jumps, weighted jumps, band-assisted vertical jump and bench presses, a 1 kg medicine ball overhead wall throw, push press, and band assisted push-ups for FCT training. These were helpful for training prescriptions and providing the participants with a better understanding of the training program. After completing the 1 RM test for each resistance training exercise, baseline tests (Time 1) were evaluated for each of the variables chosen for the study. One day before the baseline test (Time 1), the participants were instructed to refrain from indulging in any form of strenuous activity and to consume a meal that they regularly consume. End line test (Time 2) was used to assess after the commencement of 3 months of CMT and FCT training intervention. The semantic representation of the investigation explains the sample sizes in different stages (Figure 1).

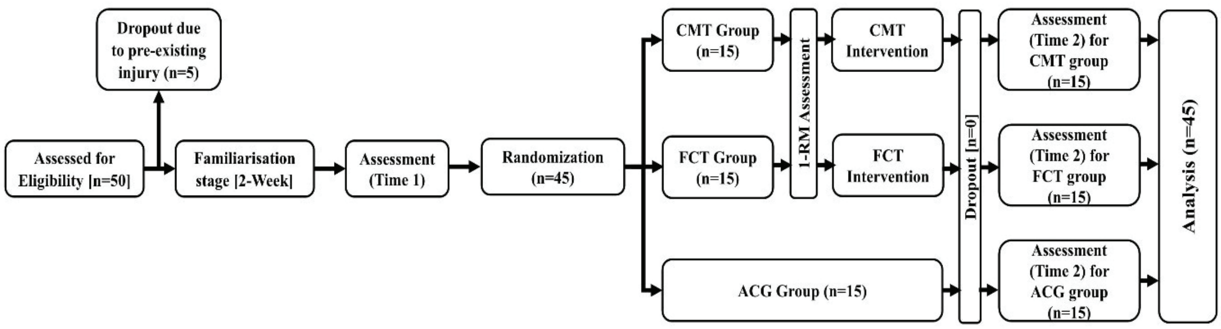

Figure 1. Semantic Representation

Intervention

CMT and FCT groups have completed three sessions per week, and 36 training sessions were given for each treatment group. Each treatment group performed standardized warming-ups and cooling down specific training programs for each group. Warming ups include general and specific for toning the muscles to perform the specific training program (CMT and FCT). CMT and FCT training were given to the subjects based on the training mentioned in the narrative review by Cormier et al. (2022). Every participant began their resistance training (high load activity) in CMT and FCT training with an intensity level of sixty per cent throughout the first few weeks of the program. From the first to three weeks, the intensity of the training ranged from sixty to seventy per cent; from the fourth to six weeks, it was sixty to seventy-five per cent; from the seventh to ninth weeks, it was seventy to eighty per cent; and from the tenth to twelve weeks, it was seventy-five to eighty-five per cent. For plyometric training (low load activities) in CMT and FCT training, first to three weeks, the intensity of the training fixed to a 12-inch box (box height) for lower extremities and l kg weight (medicine ball) for upper extremities; in the fourth to six weeks, it was an 18-inch box for lower extremities and 3 kg weight for upper extremities; in the seventh to ninth weeks, it was 24-inch box for lower extremities and 5 kg weight for upper extremities; and in the tenth to twelve weeks, it was 24 inch box for lower extremities and 5 kg weight for upper extremities. For the FCT group weighted plyometric exercise (3rd exercise), 30-40 per cent of 1 RM was fixed for 3- months, and assisted plyometrics (4th exercise) sets and repetition progressively increased. The appropriate recovery time was provided between each set and workout.

Load measurement

The 1RM test was frequently used to assess the individualized training intensities of the participants (Kumar et al., 2024). Prior to every evaluation, the participants went through a familiarization session. Additionally, general and specific warm-up, which lasted for ten to fifteen minutes, was performed before each evaluation. The weight was gradually increased to five kilograms to accomplish the 1 RM in a maximum of five attempts. There was a four-minute break in between each 1 RM effort. Spotters with experience secured the safety. The training loads for CMT and FCT were set as a percentage of each participant's 1RM to maximize strength and power gains.

Outcome measures

The outcome measures employed in this investigation provide extensive supporting data for the study's results. Metrics like speed, COD, and ME are classified as physical outcome measures. This study's physiological outcome measurements included AP, RHR, Vital capacity (VC), and $VO_{2\ max}$. In the morning before and after 3-months of intervention, a baseline (Time1) assessment and an end-line (Time2) assessment were used to look at all the outcome measures for this study. Participant height was measured using a standard stadiometer (MCP 2m/200CM Roll Ruler Wall Mounted Growth Stature Meter), weight was assessed with a digital weighing machine (HD-93), and body mass index was calculated using the formula: weight (kg) / height (m^2).

In physical outcome measures, the speed was tested with a widely used test 50m dash, which was measured in seconds (Bartosz et al., 2024; Zabaloy et al., 2021). Individualized warm-ups were followed by two 50-meter sprints on an outdoor track, with a 5 to 10-minute break. Experienced sprinters used individualized warm-ups to optimize performance and prevent injuries (Martín-Fuentes & van den Tillaar, 2022). The subjects started each sprint in a split stance, with one hand on the floor and the other behind the line, which is commonly utilized in training. Three timers were used for each attempt, and a hand stopwatch(Thapa et al., 2023) (NIVIA JS 609 Digital Stop Watch, Freewill Sports Pvt. Ltd., India) was used to obtain measures of the speed of the participants. The interclass correlation coefficient (ICC) for test-retest reliability was 0.95 (95% confidence Interval [CI]: 0.861–0.984, Coefficients of variation [CV]: 4.8% presented in table 3.

The Change of direction (COD) was evaluated using the Illinois agility test, an acceptable tool for evaluating the COD, measured in seconds (Pauli et al., 2023). The field is 10 m long and 5 m wide between start and finish positions. Four cones were positioned in the centre of the testing area, 3.3 m apart. Four cones indicated the beginning, end, and two turning places. Individualized warm-ups were followed by one trial on a specific field, with ample recovery given between trial and test. The individuals began the test lying prone, hands at shoulder level. The trial began with the "go" instruction, prompting the individuals to run as quickly as possible. The trial ended when the players crossed the finish line without knocking down cones (Cao et al., 2020). The best time from three trials was utilized for analysis (Andrašić et al., 2021). Hand stopwatch (NIVIA JS 609 Digital Stop Watch, Freewill Sports Pvt. Ltd., India) used to record the COD. The interclass correlation coefficient (ICC) for test-retest reliability was 0.98 (95% confidence Interval [CI]: 0.943–0.994, Coefficients of variation [CV]: 5.3% presented in table 3.

Finally, muscular endurance (ME) was tested with a sit-up test (Cho et al., 2024). Participants were told to lie supine with both hands folded behind their heads and legs at a 45-degree angle (Jeong & Chun, 2021). Each time the participants contacted their knee and returned to a supine posture, it was counted as one successful repetition (Zhang et al., 2021). The maximum number of repeats was timed for one minute. The interclass correlation coefficient (ICC) for test-retest reliability was 0.87 (95% confidence Interval [CI]: 0.635–0.959, Coefficients of variation [CV]: 5.8% presented in table 3.

In physiological outcome measures, the stair run test developed by Margeria Kalamen is recognized as one of the most widely used techniques for determining Anaerobic power (AP) (Cabre et al., 2024). The Margaria Kalamen stair run power test measures the time between the third and ninth steps. Participants completed a standard aerobic warm-up, stretching, and three submaximal stair runs. Participants started 6 meters from the stair base. Upon receiving the start signal, participants sprint and take three steps on the third, sixth, and ninth steps to ascend as quickly as possible. A stopwatch records the time from the third to the ninth step, beginning when the foot contacts the third step and finishing when it touches the ninth step, each step approximately 17.5 inches (Morse & Biggerstaff, 2024). Three test trials with pauses of 2-3 minutes each were allowed. The power output was calculated by the formula $P=(W*D)9.8/t$. P= Anaerobic power, W= body weight, D= vertical distance (3rd to 9th step), 9.8= gravity (constant), t= time taken (3rd to 9th step) (Pramod & K, 2023). The interclass correlation coefficient (ICC) for test-retest reliability was 0.98 (95% confidence Interval [CI]: 0.963–0.996, Coefficients of variation [CV]: 10.9% presented in table 3.

Resting heart rate (RHR) was tested with the manual radial palpation method. Because the pulse rate is identical to the heartbeat, the radial palpation approach is the most straightforward and widely utilized method, measured in numbers per minute (Cooney et al., 2010). The test was administered in the morning before any activities. The subject was sitting and resting for a minimum of five minutes when the RHR was measured. Using the tips of the index and middle fingers, find the radial artery on the thumb side of their wrist (Motimath

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& Rajan, 2020). Feel the pulse, count the beats for thirty seconds, then multiply by two to get beats/ minutes. To prevent variations in the subject's RHR, the researcher ensured that the subject remained quiet during the test. The interclass correlation coefficient (ICC) for test-retest reliability was 0.94 (95% confidence Interval [CI]: 0.834–0.982, Coefficients of variation [CV]: 2.8% presented in table 3.

Vital capacity (VC) was tested with a spirometer, measured in litres (Fabrin et al., 2023). The participants received comprehensive verbal instruction in this test before taking the exam. The participants were instructed to inhale deeply through their clipped nostrils and then exhale forcefully into the spirometer's opening. Participants had to ensure that their mouths and the spirometer's opening were tightly sealed during the test. There were three trials for each contestant. VC score was determined by taking the best of the three. The spirometer was thoroughly inspected each time in preparation for the following trial. The interclass correlation coefficient (ICC) for test-retest reliability was 0.95 (95% confidence Interval [CI]: 0.861–0.981, Coefficients of variation [CV]: 6.8% presented in table 3.

Finally, the $VO_{2\ max}$ was tested using the Queens College step test (Salehi et al., 2017). The step test was carried out from a height of 16.25 inches (Aryal et al., 2020). The stepping was done for three minutes, with a rate of twenty-four steps per minute stated. After finishing the work, the carotid pulse rate was monitored from the fifth to the thirtieth seconds of recovery. The 30-second pulse rate was translated into beats per minute. Finally, the $VO_{2\ max}$ score was calculated using the following equation: $VO_{2\ max}$ = 111.3- (0.42 x pulse rate beat/min). The interclass correlation coefficient (ICC) for test-retest reliability was 0.96 (95% confidence Interval [CI]: 0.909–0.990, Coefficients of variation [CV]: 6.8% presented in Table 3.

Statistical analysis

The Shapiro-Wilks test was used to evaluate if the data were normal after all the data had been tabulated using Microsoft Excel. Intraclass correlation coefficients were computed to ascertain the measured variables' inter-measurement reliability. In order to make sure there was no significant difference between the groups, the baseline assessment parameters of the participants (age, weight, height, and body mass index) were determined using one-way ANOVA and the Levene test. The intra-class correlation coefficients (ICCs) were used to evaluate the test-retest reliability of all tests, but only for the ACG. In terms of reliability, the inter-rater correlation coefficient (ICC) across trials and assessors was evaluated as follows: excellent (>0.9), good (0.75–0.9), moderate (0.5–0.75) and poor (<0.5). A paired sample t-test was used to compare the changes after 3- months of intervention with baseline for each of the three groups and all outcome measures. Cohen's d values, which were classified as trivial: 0 to 0.2; small: 0.21 to 0.6; moderate: 0.61 to 1.2; large: 1.21 to 2.0; very large: 2.01 to 4.0; nearly perfect: >4.01 (Ndlomo et al., 2023), were used to quantify the magnitude of changes between Time 1 and Time 2 assessment. A 3x2 (group x time) mixed design analysis of variance for repeated measures test was used to assess the changes of three groups for all outcome measures. This test measured the effects of time (Time 1 and Time 2), group (CMT, FCT, and ACG), and interaction (group x time). The Bonferroni post hoc test was utilized to identify group differences accurately. Furthermore, the two-way repeated measures ANOVA test yielded the partial eta-square (η_p^2). The effect size, or partial eta-square, was employed to ascertain the extent of the variation. The interpretations for a big are (≥0.14), a medium is (0.06-0.14), and a small is (≤0.06). Pairwise comparisons were applied with the Bonferroni post hoc test. In order to display the statistical significance, a level of 0.05 was set. All statistical analysis was done using the statistics package for social science software version 22.0.

Results

Table 1 shows the baseline characteristics of the two intervention groups (FCT and CMT) and the control group (ACG). There was no discernible difference in the participants' weight (p=.368), height (p=.281), or age (p=.827). Kolmogorov-Smirnov and Shapiro-Wilk tests were used to determine whether the participants' characteristics were normal.

Table 1. Characteristics of participants

Characteristics	CMT Mean (SD)	FCT Mean (SD)	ACG Mean (SD)	p
Weight	64.73(4.33)	65.07(6.46)	62.67(3.72)	.368
Height	1.70(.075)	1.71(.061)	1.67(.040)	.281
Age	19.47(1.19)	19.60(.986)	19.33(1.34)	.827
BMI	22.53(1.54	22.30(1.48)	22.49(.613)	.869

Table 2 demonstrates that the characteristics of the participants had Test of Homogeneity of Variances with the p values of p=.099 for weight, p=.138 for height, p=.209 for age, and p=.053 for body mass index, all of which were higher than the significance level of 0.05 (p>0.05). Same as Table 1, the Table 2 results show that the observed population has a uniform distribution for each experimental group (CMT, FCT, and ACG)

Table 3 presented that the evaluated tests' intra-class correlation coefficients (ICC) varied from 0.87 to 0.98, while the coefficients of variation (CV) ranged from 2.8 to 10.9%.

Table 2. Tests of Homogeneity for baseline characteristics of participants

Characteristics	Levene Statistic	df1	df2	sig
Weight	2.440	2	42	.099
Height	2.079	2	42	.138
Age	1.627	2	42	.209
BMI	3.156	2	42	.053

Table 3. Intraclass correlation coefficients (ICCs) for relative reliability and coefficients of variation for absolute reliability

Outcome Measures	ICC	95%CI	CV
Speed	0.95	.861-.984	4.8%
COD	0.98	.943-.994	5.3%
ME	0.87	.635-.959	5.8%
AP	0.98	.963-.996	10.9%
RHR	0.94	.834-.982	2.8%
VC	0.95	.861-.984	6.8%
$VO_{2\,max}$	0.96	.909-.990	6.8%

Table 4 displays the results of the Kolmogorov-Smirnov and Shapiro-Wilks tests used to determine the normality of the outcome measures (Speed, COD, ME, AP, RHR, VC, and $VO_{2\,max}$). The Shapiro-Wilks and Kolmogorov-Smirnov tests revealed that all outcome measure data were normally distributed.

Table 4. Tests of normality

Outcome measures	Group	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Speed	CMT	.142	15	.200	.924	15	.223
	FCT	.113	15	.200	.941	15	.389
	ACG	.152	15	.200	.934	15	.314
COD	CMT	.164	15	.200	.918	15	.178
	FCT	.133	15	.200	.926	15	.236
	ACG	.183	15	.190	.899	15	.093
ME	CMT	.212	15	.069	.910	15	.134
	FCT	.141	15	.200	.937	15	.350
	ACG	.162	15	.200	.932	15	.291
AP	CMT	.178	15	.200	.909	15	.130
	CNST	.163	15	.200	.946	15	.469
	ACG	.209	15	.076	.910	15	.134
RHR	CMT	.167	15	.200	.931	15	.279
	FCT	.217	15	.056	.937	15	.343
	ACG	.168	15	.200	.955	15	.601
VC	CMT	.185	15	.178	.900	15	.096
	FCT	.212	15	.069	.917	15	.175
	ACG	.202	15	.100	.882	15	.050
$VO_{2\,max}$	CMT	.140	15	.200	.913	15	.153
	FCT	.211	15	.071	.923	15	.217
	ACG	.142	15	.200	.924	15	.223

Table 5 displays the repeated measure analysis of variance on speed, COD, ME, AP, RHR, VC, and $VO_{2\,max}$ over two times. There were significant changes in speed between time ($p<0.01$, $\eta_p^2=.461$) with a large effect as well as between groups ($p<0.01$, $\eta_p^2=.330$) with a large effect. However, there were no significant changes between groups ($p=.280$, $\eta_p^2=.059$) with a large effect. COD had significant changes between group ($p<.001$, $\eta_p^2=.476$), time ($p<.001$, $\eta_p^2=.778$), and group x time ($p<.001$, $\eta_p^2=.669$) with large effect. ME had significant changes between group ($p<.001$, $\eta_p^2=.417$), time ($p<.001$, $\eta_p^2=.838$), and group x time ($p<.001$, $\eta_p^2=.700$) with large effect. AP had significant changes between group ($p<.001$, $\eta_p^2=.507$), time ($p<.001$, ES=.876), and group x time ($p<.001$, $\eta_p^2=.754$) with large effect. VC had significant changes between group ($p<.001$, $\eta_p^2=.546$), time ($p<.001$, $\eta_p^2=.825$), and group x time ($p<.001$, $\eta_p^2=.692$) with large effect. $VO_{2\,max}$ had significant changes between group ($p<0.01$, $\eta_p^2=.240$), time ($p<.001$, $\eta_p^2=.727$), and group x time ($p<.001$, $\eta_p^2=.565$) with large effect. Finally, RHR showed no significant difference between group, time and group x time at 0.05.

When considering the paired sample t-test presented in a table, speed had a significant difference in CMT ($p<0.01$, d=1.03) with a moderate effect and FCT ($p<.001$, d=1.31) group with a significant effect. However, the ACG group showed no significant difference ($p>0.05$). COD had a significant difference in CMT ($p<0.05$, d=.579) with a small effect and FCT ($p<.001$, d=1.45) group with a significant effect, but the ACG group did not show any significant difference ($p>0.05$). ME had a significant difference in CMT ($p<.001$, d=2.35) with a substantial effect and FCT ($p<.001$, d=3.44) group with a very

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Table 5. Repeated measures ANOVA

Outcome measures	Group	Time 1 (SD)	Time 2 (SD)	Group (effect)	Time (effect)	Group x time (interaction)
				P (ηp2) 95%CI		
Speed	CMT	7.36(.377)	7.04(.180)	.280 (059)	.000** (.461)	.000** (.330)
	FCT	7.36(.380)	6.97(.183) ▲			
	ACG	7.32(.331)	7.33(.304) ▲			
COD	CMT	18.61(1.02)	17.63(1.15)	.001** (.271)	.000** (.331)	.000** (.276)
	FCT	18.61(1.08)	16.54(1.10) ▲			
	ACG	18.65(1.01)	18.72(.983) ▲			
ME	CMT	39.87(2.45)	47.53(4.34)	.000** (.417)	.000** (.838)	.000** (.700)
	FCT	40.73(2.68)	51.53(3.44)▲			
	ACG	40.33(2.61)	40.93(2.71) ▲			
AP	CMT	1072.81(91.90)	1425.76(104.23)	.000** (.507)	.000** (.876)	.000** (.754)
	CNST	1075.27(130.80)	1531.10(110.32) ▲			
	ACG	1073.18(96.30)	1099.75(112.71) ▲			
RHR	CMT	74.27(2.49)	73.73(2.25)	.317 (.053)	.662 (.005)	.052 (.131)
	FCT	74.27(2.37)	73.47(1.92)			
	ACG	74.53(3.07)	75.47(2.33)			
VC	CMT	3.83(.243)	4.51(.194)	.000** (.546)	.000** (.825)	.000** (.692)
	FCT	3.81(.273)	4.73(.158) ▲			
	ACG	3.77(.263)	3.81(.252) ▲			
$VO_{2\,max}$	CMT	39.31(2.51)	43.93(1.81)	.003* (.240)	.000** (.727)	.000** (.565)
	FCT	39.26(2.62)	46.17(1.75) ▲			
	ACG	39.76(3.05)	40.04(2.80) ▲			

**Significant at .001, *Significant at 0.05, ▲ Significant difference with control 0.05

large effect, but the ACG group did not show any significant difference (p>0.05). AP had a significant difference in CMT (p<.001, d=2.69) with a substantial effect and FCT (p<.001, d=4.46) group with a nearly perfect effect. However, the ACG group showed no significant difference (p>0.05). VC had a significant difference in CMT (p<.001, d=2.87) with a substantial effect and FCT (p<.001, d=2.86) group with a very large effect, but the ACG group did not show any significant difference (p>0.05). $VO_{2\,max}$ had a significant difference in CMT (p<.001, d=1.63) with a large effect and FCT (p<.001, d=2.85) group with a very large effect, but the ACG group did not show any significant difference (p>0.05). RHR did not show any significant difference between all the three groups. The magnitude of the effect is presented in Figure 2.

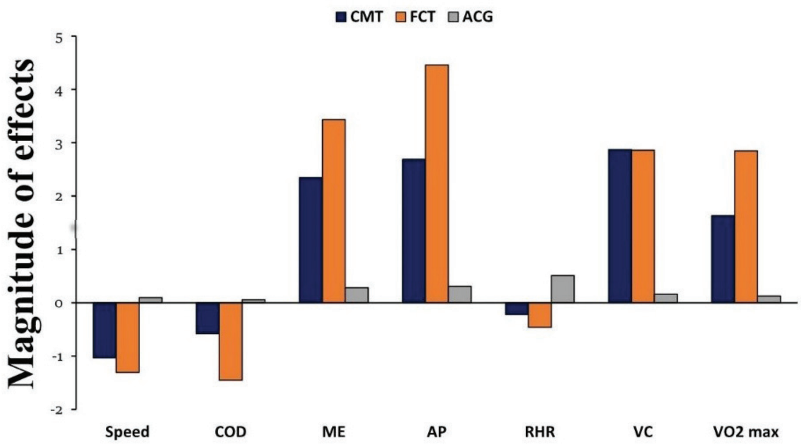

Figure 2. Magnitude of effects on Time 1 to Time 2 for the selected outcome measures

When considering the one-way analysis of variance, time 1 assessment of all the outcome measures did not show any significant difference at the 0.05 level. Time 2 assessment on speed, COD, ME, AP, VC, and $VO_{2\,max}$ significantly improved in both training interventions (CMT and FCT). However, RHR did not show any significant improvement in both training interventions (CMT and FCT) and the ACG group.

When considering the Bonferroni post hoc test (table 7), the FCT group showed significantly higher improvement in COD, ME, AP, VC, and $VO_{2\,max}$ when compared to the CMT group. Moreover, FCT and CMT groups significantly improved speed, COD, ME, AP, VC, and $VO_{2\,max}$ at p<.001, and RHR at .05 levels.

Table 6. Paired t-test

Outcome measures	Group	df	T-Ratio	p	Cohen's d
Speed	CMT	14	3.991	.001*	1.03
	FCT	14	5.056	.000**	1.31
	ACG	14	.372	.716	0.10
COD	CMT	14	2.243	.042*	.579
	FCT	14	5.61	.000**	1.45
	ACG	14	.222	.828	.057
ME	CMT	14	9.092	.000**	2.35
	FCT	14	13.303	.000**	3.44
	ACG	14	1.090	.294	0.28
AP	CMT	14	10.417	.000**	2.69
	CNST	14	17.267	.000**	4.46
	ACG	14	1.191	.253	0.31
RHR	CMT	14	.845	.413	0.22
	FCT	14	1.780	.097	0.46
	ACG	14	1.974	.068	0.51
VC	CMT	14	11.129	.000**	2.87
	FCT	14	11.075	.000**	2.86
	ACG	14	.627	.541	0.16
$VO_{2\,max}$	CMT	14	6.323	.000**	1.63
	FCT	14	11.028	.000**	2.85
	ACG	14	.495	.628	0.13

*Significant at 0.05, **significant at 0.001.

Table 7. Post Hoc Comparison

Outcome measures	Groups		Mean difference	SE	P_B	95% Confidence Interval for Difference	
						Lower Bound	Upper Bound
Speed	CMT	FCT	.072	.060	.702	-.077	.222
	CMT	ACG	-.304	.060	.000**	-.454	-.154
	FCT	ACG	-.376	.060	.000**	-.526	-.227
COD	CMT	FCT	1.090	.399	.028*	.094	.2.087
	CMT	ACG	-1.084	.399	.029*	-2.080	-.087
	FCT	ACG	-2.174	.399	.000**	-3.171	-1.177
ME	CMT	FCT	-3.286	1.066	.011*	-5.948	-.625
	CMT	ACG	6.984	1.059	.000**	4.342	9.627
	FCT	ACG	10.271	1.058	.000**	7.630	12.911
AP	CMT	FCT	-104.088	34.882	.014*	-191.162	-17.015
	CMT	ACG	326.204	34.881	.000**	239.134	413.273
	FCT	ACG	430.292	34.882	.000**	343.220	517.364
RHR	CMT	FCT	.267	.600	1.000	-1.232	1.765
	CMT	ACG	-1.589	.601	.035*	-3.088	-.089
	FCT	ACG	-1.855	.601	.011*	-3.355	-.356
VC	CMT	FCT	-.235	.070	.005*	-.409	-.061
	CMT	ACG	.683	.070	.000**	.509	.858
	FCT	ACG	.918	.070	.000**	.744	1.093
$VO_{2\,max}$	CMT	FCT	-2.250	.695	.007*	-3.985	-.516
	CMT	ACG	4.076	.696	.000**	2.338	5.814
	FCT	ACG	6.326	.697	.000**	4.587	8.066

*Significant at 0.05, **significant at 0.001.

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Discussion

The present study aimed to investigate the effects of three weekly training sessions of CMT and FCT on the physical and physiological outcomes measures of field hockey players, and the secondary aim of the study compared the effects of three weekly training sessions of CMT versus FCT on physical and physiological outcome measures of field hockey players. The results revealed significant improvements in physical performance measures, including speed and COD, as well as physiological parameters such as AP, VC, and $VO_{2\,max}$. Additionally, it was discovered that the FCT had improved more in all of the selected physical outcome measurements, including speed and COD, as well as the majority of the physiological outcome measurements, including AP, VC, and $VO_{2\,max}$.

CMT and FCT responses on physical measures

The results of the present study reveal that CMT and FCT significantly improved speed, COD, and ME in physical outcome measures compared to the control group. One of the main outcomes of the present study was consistent with earlier CMT studies in field hockey players (Koca & Recvan, 2023; Thapa et al., 2023). Athletes can acquire the precise physical traits essential for best performance by concentrating on high-intensity, short-duration workouts that simulate the demands of actual match play. These activities include linear sprinting, agility, and maximal isokinetic strength. This method is consistent with the findings presented by Thapa (2023) and lends credence to the idea that strategic supplemental training treatments can bring about considerable enhancements in field hockey players. Specific neuromuscular adaptations may be responsible for performance improvement in the CMT and FCT groups. These adaptations may have resulted in an improved stretch-shortening cycle (SSC), increased motor unit recruitment, firing frequency, intra- and inter-muscular coordination, and alterations in structure that assist with the ability to produce the greater force from the muscle (Cormier et al., 2020). The results of Koca and Recvan (2023) suggest that the resistance training, which was applied three days a week for eight weeks and consisted of a strength training program with an intensity of 50–70% 1 RM and free weight exercises, core exercises, and resistance band exercises, significantly increased the muscular strength and ME of both male and female field hockey players. Some of the findings from earlier research align with the current study's results, which were conducted with a different population (Ali et al., 2019; Kumar et al., 2023; Nasrulloh et al., 2022). Ali et al. (2019) reveal that after participating in a training program that lasted for six weeks, football players experienced increased agility and speed due to CMT. Likewise, a comparison was made by Kumar et al. (2023) between the effects of load-equated two and three-complex contrast training sessions per week on several measures of physical fitness. Compared to the complex contrast training, which was two sessions per week, the complex contrast training, which was three sessions per week, resulted in much better improvements in speed and COD.

Further promoting the activation of fast-twitch muscle fibres, this force-velocity relationship optimization may aid in maximizing athletic performance like sprints and COD speed (Cormier et al., 2022). The study by Nasrulloh et al. (2022) explores that Archery athlete's ME is significantly increased by weight training using the compound set approach, which consists of an intensity of 60-80% 1 RM, 3-4 sets, and 15-25 reps. Therefore, weight training with the compound set approach over eight training weeks may significantly improve an archery athlete's strength and ME. This study found that increased muscle endurance following 3-months of intensive training. Improved neuromuscular efficiency helps the nervous system activate muscles and coordinate (Hammami et al., 2019; Josef, 2018). Resistance workouts develop muscular fibres, causing muscle hypertrophy and sustained muscle activity(Currier et al., 2023). Enhanced motor unit synchronization and activation lead to increased motor unit recruitment (Grgic et al., 2021). Muscles adapt to carry more weight for longer durations, increasing endurance (Rathi et al., 2023). The above factors may have contributed to this present study's excellent outcomes.

According to the current research findings, the FCT led to considerable gains in terms of speed, COD, and ME when compared to the CMT in terms of assessment of physical outcomes. Although there is a paucity of published material on FCT for hockey athletes, the findings presented here are consistent with those of earlier research carried out on a variety of sports populations that share comparable traits or characteristics (Türkarslan & Deliceoğlu, 2024). When applied to professional soccer players, the FCT program can potentially boost speed throughout a training program that lasts for three weeks (Türkarslan & Deliceoğlu, 2024). The FCT for ten weeks increased the power and performance of complex skills for football players. These skills include speed and skill performance (receiving and running with the ball, receiving, dribbling passing, receiving, dribbling shooting)(Salam & Sherif, 2020). In order to achieve this, football players must have efficient speed, trunk strength, and agility abilities (França et al., 2022; Saeterbakken et al., 2022; Viran et al., 2022). Among the four different CMT strategies offered to have the best potential influence on the PAPE phenomenon is the FCT Method (Rebelo et al., 2023; Türkarslan & Deliceoğlu, 2024). They are targeting four components of the force-velocity relationship. That is, in the precise order: maximum strength, speed-strength, strength-speed, and maximum speed, respectively. The goal is to elicit a PAPE with the contrasting nature of loading/contraction types (Cormier et al., 2022). Some studies have explored that PAPE protocols show performance benefits in agility tests and sprint tests (Escobar Hincapié et al., 2021; Thapa et al., 2020).

CMT and FCT responses on physiological measures.

The findings of the current research indicate that both CMT and FCT led to substantial improvements in physiological outcome measures such as AP, VC, and $VO_{2\,max}$ when compared to the group that served as the control. RHR did not show any significant difference between the treatment group and the control group. Regarding those outcome measures, FCT demonstrated a greater degree of improvement than CMT. Published research on FCT for hockey players lacks physiological outcome measures (K V et al., 2024). The study by K V et al., (2024) indicates that over the period of 12-week FCT intervention (36 trining sessions) effectivly enhances the AP, and VC. Moreover, the results shown here align with other studies conducted on different populations (Chang et al., 2022; Ingle et al., 2006). Chang et al. (2022) imply that eight weeks of classical resistance training substantially improved AP for healthy college students.

Similarly, Ingle et al. (2006) found that CMT increased the average AP throughout a twelve-week intervention. It might be the consequence of High-load activity may increase calcium in the muscle fibre's myoplasm, activating the myosin light chain kinase, which phosphorylates the light chains and promotes actin-myosin cross-bridges, which potentiates lower-load activity (Cormier et al., 2022). One of the studies that Ağirbaş and Karakurt (2023) carried out was to investigate the impact that static strength training using a Tera-Band for the upper extremities had on the ability of the lungs to breathe. It revealed that static strength training performed with a Tera-Band for the upper extremities affected the respiratory capacities of elite boxers, such as their forced vital capacity (Ağirbaş & Karakurt, 2023). Similarly, the forced vital capacity increased after six weeks of plyometric training in aerobic gymnasts (Cuce et al., 2021).

Regarding $VO_{2\ max}$, Chovanec and Gröpel (2020) reported that the resistance training program resulted in physiological adaptation, which manifested itself as an increase in $VO_{2\ max}$ following the intervention that lasted for eight weeks for the training program (Chovanec & Gröpel, 2020). In CMT and FCT training, high-intensity efforts are combined with incomplete rest intervals (Cormier et al., 2022). This combination results in a more significant strain on the circulatory system and an improvement in the efficiency with which oxygen is utilized. Because of the fatigue that results, the body is forced to adapt by improving its cardiorespiratory function and increasing the amount of oxygen uptake to meet the increased demands (Kayhan et al., 2024). These physiological changes support higher levels of athletic performance, leading to increased vital capacity and voluntary oxygen consumption ($VO_{2\ max}$) (Monnerat et al., 2020). This may be the reasonable rationale for improving vital capacity and $VO_{2\ max}$ following the systematic implementation of CMT and FCT training intervention.

Additionally, the current study revealed that the CMT and FCT were unsuccessful in improving the RHR compared to the ACG. According to the findings of research conducted by Rathi et al. (2023), complex-descending training over six weeks does not result in a substantial reduction in RHR (Rathi et al., 2023). According to one of the Mata analyses, strength training does not substantially influence the RHR (Reimers et al., 2018). The athletes had previously surpassed the targeted threshold by continuous engagement, which is the most plausible explanation for the result (Rathi et al., 2023).

Limitation

A few restrictions should be taken into consideration regarding this study. Due to the limited amount of information available in this sector, comparing the present findings with those of previous FCT research conducted in hockey is not feasible. This study, on the other hand, will serve as a foundation for further research on hockey players since it presents original and innovative evidence. Additionally, the duration of the training intervention was restricted to twelve weeks. More extended research beyond three months may be required to assess the long-term adaptations in hockey athletes. Despite considerable gains being shown in the CMT and FCT groups, one of the outcome measures, RHR, did not show any significant decline. The third limitation is that the sample size for this research needed to be more significant. A higher sample size may be necessary in order to validate the findings that have been obtained. Finally, data about biochemistry or haematology needs to be collected. These data would give additional insights into the biological elements of the training, which could increase the evidence of the interconnection of the selected outcome measures and the effect of the specified training interventions.

Practical application

Within the context of field-based team sports, the practical implications of our study findings are pertinent for fitness experts and coaches interested in optimizing exercise programmes to improve physical fitness and overall health through physiological markers. As a result of the fact that both CMT and FCT displayed substantial improvements in speed, COD, and ME, it is evident that adopting either training modality into a daily exercise programme can successfully create favourable changes in overall fitness and development in sport-specific skills. This understanding can be helpful for fitness experts when they are developing individualized exercise programmes to improve physiological markers so that they can attain cardiorespiratory health. Furthermore, coaches and strength and conditioning trainers may utilize this information to offer suggestions for athletes looking to enhance their general health, particularly those who participate in team sports. Data can justify these recommendations.

Conclusion

The potential for physical and physiological outcome measures was investigated to improve field hockey players following a 3-month CMT or FCT training plan. After completing a 3-month CMT and FCT training course, we conclude that participants in both training groups improved more in speed, direction changes, and muscle endurance (compared with ACG). After completing a 3-month CMT and FCT training program, we conclude that individuals in both training groups improved more in VC, AP, and $VO_{2\ max}$ in physiological end measures (when compared with ACG). The ACG and the two-intervention group's RHR did not alter significantly. Moreover, when comparing the FCT group to the CMT group, it was revealed that the FCT group had improved more in all of the chosen physical outcome measures and most of the physiological outcome measurements, except RHR.

Consequently, if boosting COD speed, ME and VC, AP, and $VO_{2\ max}$ are targets, practitioners and coaches may choose CMT and FCT programs. Finally, trainers, coaches, and athletes who wish to enhance their routines are advised to try FCT. Such integration facilitates the intended modifications in physiological and physical factors beyond CMT training, significantly improving hockey players' overall performance and success.

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Conflicts of interest

The authors declare that there are no conflict of interest.

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ORIGINAL SCIENTIFIC PAPER

Comparison of the Active Drag and Passive Drag Coefficients at the same Swimming Speed Through Experimental Methods

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Abstract

Studies about drag in swimming usually report or put the focus on its absolute value. However, it is being claimed that the drag coefficient better represents the hydrodynamic profile of a swimmer. Drag is strongly dependent on speed. Thus, increases in speed will lead to increases in drag. This could lead to misleading interpretations since drag is the water resistance that makes the swimmers' displacement difficult. Conversely, the drag coefficient is less dependent on speed, which can be seen as a more appropriate measure of the swimmers' hydrodynamic profile. This study used a complete experimental methodology (experimental and cross-sectional study) to determine the resistive forces in crawl swimming at the same speed (i.e., 1.00, 1.05, 1.10 m/s, etc.). In 10 proficient non-competitive adult swimmers (seven men and three women), the drag coefficient (C_D) was compared and the difference between using the technical drag index (TDI) with drag (D, passive or active) or with its respective C_D 's. Measurements of active drag (D_A), passive drag (D_P) and C_D (C_{DA} and C_{DP}) were carried out. The TDI was calculated as a measure of swimming efficiency and the frontal surface area (FSA) obtained in active conditions. The active FSA was 20.73 ± 5.56% greater than the passive FSA (large effect size), the propulsion was 58.29 ± 69.61% greater than drag and C_{DA} was 24.60 ± 46.55% greater than C_{DP} (moderate effect size). TDI was significantly lower, but with a small effect size when measured with C_D values compared to drag. TDI_D vs TDI_{CD} revealed strong agreement (> 80% of plots were within IC95). This study concludes that proficient swimmers presented a C_{DA} greater than the CDP, but with strong agreement between them, probably due to FSA during active conditions. C_D data appears to be a more absolute indicator of drag than TDI.

Keywords: *human body, practical methodology, resistive forces, biomechanics, technique*

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Introduction

Swimming speed depends on the interaction between propulsive and resistive forces (also known as drag) (Toussaint and Beek, 1992). Propulsive forces refer to the force generated by the swimmer through the actions of the upper and lower limbs to promote forward motion (Berger, 1999). Conversely, drag is the water resistance to a swimmer moving through water (Vogel, 1994). This can be expressed by Newton's equation as:

$$D = \frac{1}{2} \cdot v^2 \cdot \rho \cdot S \cdot C_d \qquad (1)$$

where D is the drag force (in N), ρ is the water density (in kg/m^3), υ is the swimming speed (in m/s), S is the projected frontal surface area (FSA) of swimmers (in m^2) and C_D is the drag coefficient (changing according to shape, orientation and Reynolds number). Drag can be passive (D_P – force produced during the displacement of a towed body) (Pendergast et al., 2006), or active (D_A – water resistance induced in a body during swimming) (Kolmogorov and Duplishcheva, 1992).

Literature has been reporting that D_A is about 1.5 to 2.0 times larger than D_P in the front-crawl stroke (Cortesi et al., 2024; Gatta et al., 2016; Narita et al., 2017). If, on one side, the towing test can be considered the gold standard for measuring D_P, several methods are used to measure or estimate D_A (Kolmogorov and Duplishcheva, 1992; Narita et al., 2017). For instance, in a recent study, full and semi-tethered tests were carried out based on the residual thrust method (Cortesi et al., 2024). However, one can still argue that: (i) any method that doesn't allow the swimmers to swim "freely" may provide some mechanical constraint, and; (ii) this comparison must be done at the same speed. Additionally, new trends in swimming hydrodynamics highlighted that the drag coefficient (C_D; passive – C_{DP}; or active – C_{DA}) should be the parameter to consider when analyzing the swimmers' hydrodynamic profile (Morais et al., 2024). This occurs because the C_D is less dependent on speed than drag (Kolmogorov and Duplishcheva, 1992; Vilas-Boas et al., 2010). As far as our understanding goes, there is still scarce evidence about the comparison between the C_{DP} and C_{DA} at the same speed which can bring new insights about the swimmers' hydrodynamics.

Additionally, the technique drag index (TDI) is considered a proxy of swimming efficiency by considering the ratio of D_A to D_P (Kjendlie and Stallman, 2008). For instance, if two swimmers present a similar D_P, the one with a smaller D_A could be considered as having a better swimming technique (Barbosa et al., 2013; Kjendlie and Stallman, 2008). Comparing the TDI based on drag and based on the C_D will also give insights about the importance of using the C_D as the most indicated parameter of swimming hydrodynamics.

Therefore, the aim of this study was to compare the C_{DP} with the C_{DA} in the front-crawl stroke at the same speed and understand the difference of using the TDI with drag (passive or active) or with their respective C_D's. It was hypothesized that the C_{DA} would be meaningfully greater than the C_{DP} at the same speed, and that this difference would be like the one verified between propulsion and drag. Also, the TDI based on drag would be meaningfully greater than when based on the C_D.

Methods

Participants

The sample was composed of 10 adult proficient non-competitive swimmers (seven males and three females: 20.7±1.9 years, 71.7±8.6 kg of body mass, 175.1±7.8 cm of height, 174.6±8.0 cm of arm span, and a 25 m performance of 20.25±2.72s in a 25 m sprint test with an in-water push-off start). Participants were engaged in a twice-weekly (three hours) swimming lesson program. All had a background in swimming with 4.1±2.2 years of practice. All procedures were in accordance with the Declaration of Helsinki regarding human research. A written consent form was provided and the Polytechnic Ethics Committee approved the research design (N.º 72/2022).

Research Design

After a 10-minute in-water warm-up and 5-minute dry-land stretching, the participants were invited to perform three maximal trials of 25-m in front-crawl stroke with a push-off start. The trials were spaced by an interval of 30 minutes. The fastest trial was used for further analysis. Only data between the 10th and 20th meter marks were analyzed to avoid the advantage gained in the push-off start. In active (while swimming) and passive (towed) conditions, the participants were instructed to perform non-breathing strokes or to hold their breath after maximal inspiration. Figure 1 depicts an example of a swimmer being towed (i.e., passive drag).

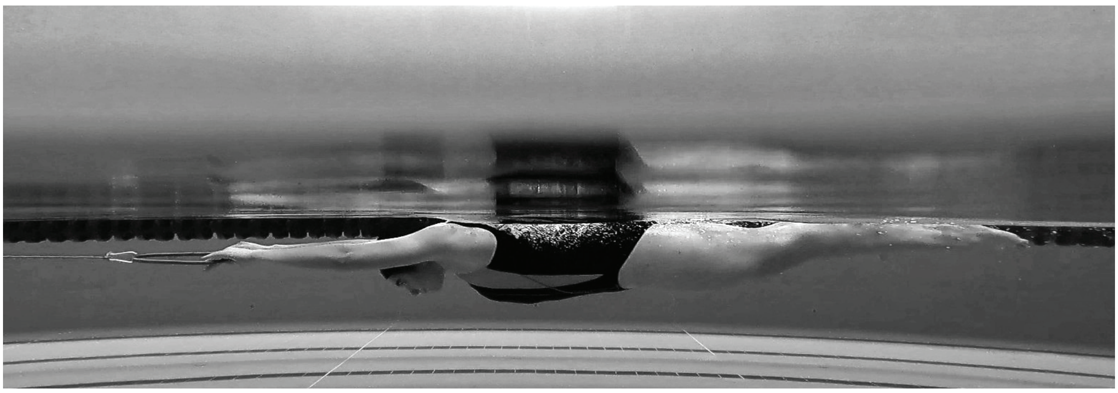

Figure 1. Illustration of a swimmer being towed for the passive drag measurement.

Technique Drag Index

The technique drag index (TDI) was calculated as a measure of swimming efficiency (Kjendlie and Stallman, 2008):

$$TDI = \frac{D_A}{D_P} \qquad (2)$$

The TDI refers to the technique drag index (dimensionless), D_A refers to active drag or active drag coefficient (N or dimensionless, respectively), and D_P to passive drag or passive drag coefficient (N or dimensionless, respectively). This was done for the drag values in passive and active conditions and respective C_D's.

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Thus, TDID refers to the TDI when absolute drag values are used, and TDI_{CD} refers to the TDI when the respective C_D is used.

Measurement of the Active Drag Coefficient (C_{DA})

The C_{DA} was calculated based on equation (1). Studies have shown that propulsion data can be used to replace drag data in such equation to calculate the C_{DA} (Havriluk, 2007; Morais et al., 2023). Propulsion was measured with wearable sensors (SmartPaddles®, Trainesense, Tampere, Finland) (Lopes et al., 2023). The sensors were attached to the swimmers' hands with silicon straps. Figure 2 depicts the sensor positioning.

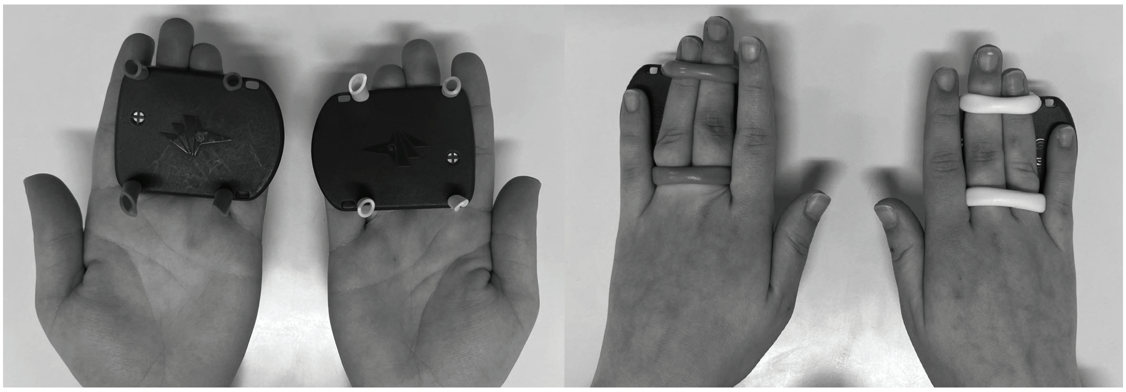

Figure 2. Positioning of the sensors.

The average propulsion of both upper limbs' arm-pulls performed between the 10th and 20th meter marks was retrieved from the database PoolShark Session Manager (https://sharksensors.com/). Afterwards, the total propulsion (P_{total}, in N) was calculated as the sum of the right and left arm-pulls. At the same time, the participants were attached to a speedometer string (SpeedRT, ApLab, Rome, Italy) to measure the swimming speed (in m/s). Afterwards, the speed-time series were imported into signal processing software (AcqKnowledge v. 3.9.0, Biopac Systems, Santa Barbara, USA). The signal was handled with Butterworth 4th order low-pass filter (cut-off: 5Hz). A video camera (GoPro Hero Black 7, USA) was placed in a fixed position in the mid-section of the swimming pool to record the swimmers in the sagittal plane and identify the hand entry. By doing this, it was possible to synchronize propulsion and speed data.

For the FSA measurement in active conditions, the participants were instructed to lie down on a bench in their swimsuits, with cap and goggles in the following positions: (i) right hand catch; (ii) right hand insweep; (iii) right hand exit and left hand catch; (iv) left hand insweep, and; (v) left hand exit and right hand catch (Lopes et al., 2023). Swimmers were photographed with a digital camera (Sony a6000, Tokyo, Japan) in the transverse plane (upward view) near a 2D calibration object. Then, each FSA position was measured by digital photogrammetry with dedicated software (Udruler, AVPSoft, USA). Afterwards, values at each position were interpolated using a cubic spline from which the FSA values were calculated at each 5% point of the stroke (Morais et al., 2020). The average value was used for further analysis.

Measurement of the Passive Drag (D_P) and Passive Drag Coefficient (C_{DP})

After knowing the swimmers' average swimming speed (i.e., during a maximal trial at front-crawl) between the 10th and 20th meter marks, the swimmers' D_P was measured at the same speed. For this purpose, the participants were attached via a nonelastic wire to a low-voltage isokinetic engine (Ben Hur, ApLAb, Rome, Italy) and were towed at a constant speed (Gatta et al., 2013). The participants were asked to (i) adopt a streamlined and hydrodynamic position, (ii) hold on to the wire, and; (iii) hold their breath after a maximal inspiration (Gatta et al., 2013). The lower limbs were passively lifted using a standard figure-eight-shaped pull-buoy (Golfinho, Portugal). As the software only allows the use of speeds every five hundredths (i.e., 1.00, 1.05, 1.10 m/s, etc), the swimmers' towing speed was set to the nearest value. Afterwards, data were handled with signal processing software as aforementioned. The average force between the 10th and 20th meter marks was used for analysis (Gatta et al., 2013; Zamparo et al., 2009). Afterwards, the C_{DP} was calculated based on equation (2). The FSA measurement for the C_{DP} calculation was done as previously described but with swimmers in an upright and hydrodynamic position. This position is characterized by the arms being fully extended above the head, one hand above the other, fingers also extended close together, and the head in a neutral position.

Statistical Analysis

The Shapiro-Wilk and the Levene tests were used to assess the normality and homoscedasticity, respectively. The mean plus one standard deviation (SD) and the relative difference (Δ, in %) were computed as descriptive statistics. The magnitude of the difference between C_D's was calculated with the paired samples t-test ($p<0.05$). Cohen's d estimated the standardized effect sizes, and deemed as: (i) trivial if $0 \leq d < 0.20$; (ii) small if $0.20 \leq d < 0.60$; (iii) moderate if $0.60 \leq d < 1.20$; (iv) large if $1.20 \leq d < 2.00$; (v) very large if $2.00 \leq d < 4.00$; (vi) nearly distinct if $d \geq 4.00$ (Hopkins, 2019). Bland-Altman analysis included the plots of the difference and average of the C_{DA} against the C_{DP}, and the TDI_D against the TDI_{CD} (Bland and Altman, 1986). For qualitative assessment, it was considered that at least 80% of the plots were within the ±1.96 standard deviation of the difference (95% confidence intervals – 95CI).

Results

Table 1 presents the descriptive statistics of all variables measured. The FSA_{active} was 20.73±5.56% larger than $FSA_{passive}$, propulsion was 58.29±69.61% greater than drag, and C_{DA} was 24.60±46.55% greater than C_{DP}. The pairwise comparisons are presented in Table 2. The FSA_{active} was significantly larger

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with a large effect size than the FSApassive (mean difference= 0.0189, 95CI=0.0160 to 0.0218, d=1.88). The propulsion was also greater with a moderate effect size than drag for the same speed (mean difference= 14.48, 95CI=2.20 to 26.77, d=1.18). As for the C_D, the C_{DA} was significantly greater with a moderate effect size than the C_{DP} for the same speed (mean difference= 0.12, 95CI= -0.07 to 0.30, d=0.62). The TDI was significantly smaller but with a small effect size when measured with the C_D's values in comparison to drag (mean difference= -0.34, 95CI= -0.52 to -0.16, d=0.53) (Table 2).

Table 1. Descriptive statistics (mean ± standard deviation) of all variables measured with 95% confidence intervals (95CI). It also presents the relative difference between FSA's, propulsion and drag, and respective coefficients

	Mean	SD	95CI	Relative Difference [%]
Swimming speed [m/s]	1.25	0.14	1.15 to 1.35	
FSA_{active} [m^2]	0.098	0.009	0.092 to 0.105	20.73 ± 5.56
$FSA_{passive}$ [m^2]	0.079	0.012	0.071 to 0.088	
Propulsion [N]	52.48	9.78	45.48 to 59.48	58.29 ± 69.61
Passive drag [N]	37.99	14.38	27.71 to 48.28	
C_{DA} [dimensionless]	0.71	0.22	0.56 to 0.87	24.60 ± 46.55
C_{DP} [dimensionless]	0.60	0.12	0.51 to 0.68	
TDI_D [dimensionless]	1.58	0.73	1.06 to 2.11	19.69 ± 4.83
TDI_{CD} [dimensionless]	1.25	0.49	0.90 to 1.60	

Note: FSA_{active}: frontal surface area measure while swimming; $FSA_{passive}$: frontal surface area while towed; C_{DA}: active drag coefficient; C_{DP}: passive drag coefficient; TDI_D: technique drag index considering drag; TDI_{CD}: technique drag index considering the drag coefficient.

Table 2. Paired samples t-test comparison between variables related to the swimmers' hydrodynamics

	t-test (p-value)	MD	95CI	d [descriptor]
FSA_{active} vs $FSA_{passive}$ [m^2]	14.69 (<0.001)	0.019	0.016 to 0.022	1.88 [large]
Propulsion vs Drag [N]	2.67 (0.026)	14.48	2.20 to 26.77	1.18 [moderate]
C_{DA} vs C_{DP} [dimensionless]	1.42 (0.189)	0.12	-0.07 to 0.30	0.62 [moderate]
TDI_D vs TDI_{CD} [dimensionless]	-4.24 (0.002)	-0.34	-0.52 to -0.16	0.53 [small]

Note: FSA_{active}: frontal surface area measure while swimming; $FSA_{passive}$: frontal surface area while towed; C_{DA}: active drag coefficient; C_{DP}: passive drag coefficient; TDI_D: technique drag index considering drag; TDI_{CD}: technique drag index considering the drag coefficient. MD: mean difference; 95CI: 95% confidence intervals; d: Cohen's effect size.

Figure 3 depicts the Bland-Altman analysis of the C_{DA} against the C_{DP} (panel A), and the TDI_D against the TDI_{CD} at the same speed. In both cases, more than 80% of the plots were within the 95CI revealing a strong agreement between variables.

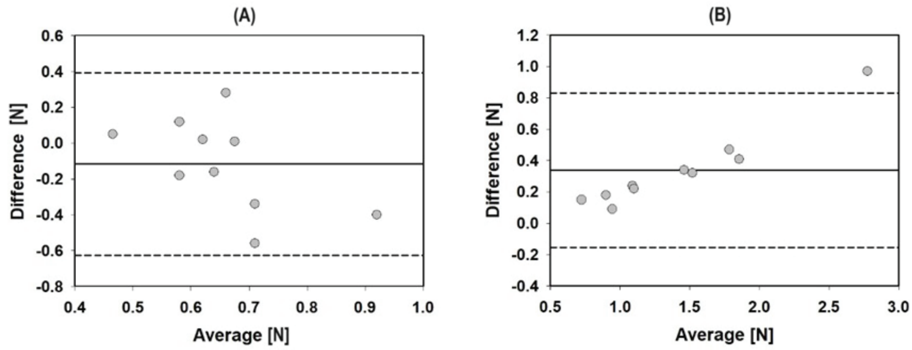

Figure 3. Bland Altman plots of the CD's (panel A) and the TDI (panel B). Dash lines refer to the 95% confidence intervals.

Discussion and Implications

The main aim of this study was to compare the C_{DP} with the C_{DA} at the same speed in the front-crawl stroke and understand the difference between using the TDI with drag (passive or active) and with their respective C_D's. The main findings were that proficient swimmers showed a larger C_{DA} in comparison to C_{DP}. Despite the non-significant differences noted, the effect size was moderate. The main reason for this could be the significant difference (with a large effect size) of the FSA noted in both conditions (larger in active than in passive). Also, the TDI calculated based on the C_D's revealed to be significantly smaller than with the drag values.

The methods used to determine C_D in both active and passive conditions are commonly reported in the literature (Gatta et al, 2016; Lopes et al., 2022; Vilas Boas et al., 2010). Regarding the active condition, the C_{DA} was calculated based on equation (1) in agreement with the fact that data related to propulsion can be used to replace the drag data in this equation to calculate the C_{DA} (Havriluk, 2007; Morais et al., 2023). The swimmers' C_{DP} was calculated based on the same equation

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where the drag value was obtained by a passive towing method (Cortesi et al., 2024; Scurati et al., 2019). This was done at the same speed as the speed measured while swimming during a maximal trial.

However, while the use of propulsion-related data to estimate the C_{DA} is supported in the literature (Havriluk, 2007; Morais et al., 2023), it is crucial to recognize the potential limitations and disputes concerning this approach. Specifically, the replacement of drag data with propulsion data in equation (1) may not fully capture the hydrodynamic differences between active and passive conditions. The C_{DA} is influenced by dynamic factors such as changes in body position and limb movement, which are not fully accounted for when using propulsion data alone. This could lead to discrepancies between the C_{DA} and C_{DP} that may not be solely attributable to differences in swimmer technique or body position, but rather to the inherent differences in the way these metrics are calculated. Furthermore, the passive towing method used to calculate the C_{DP} may oversimplify the drag experienced by a swimmer in a static position, failing to consider the complexities introduced by active swimming motions (Cortesi et al., 2024; Scurati et al., 2019). Therefore, while these methods are commonly used, they may introduce biases that need careful consideration when interpreting results.

Literature reports evidence about the methods used to measure drag (Havriluk, 2007). There are four methods to measure DA: (i) measurement of active drag (MAD); (ii) small perturbation method (SPM), also known as velocity perturbation method (VPM); (iii) assisted towing method (ATM), and; (iv) measurement of residual thrust (MRT) (Lopes et al., 2022). Overall, it was considered that despite there is no agreement among methods, they all measure the same phenomenon but in a different way (Lopes et al., 2022).

As aforementioned, the idea that the D_A is about 1.5 to 2.0 times larger than D_P seems to be consistent in the literature (Cortesi et al., 2024; Gatta et al., 2016; Narita et al., 2017). For instance, the authors plotted the DP and D_A values of six male competitive swimmers between 1.0 and 1.4 m/s for the active condition, and between 0.9 and 1.5 m/s for the passive condition (Narita et al., 2017). The authors noted that for similar speeds, the D_A tended to be greater in D_A in comparison to D_P, and this difference increased with speed (Narita et al., 2017). On the other hand, it was claimed that most research on swimming does not report the C_D's, particularly in active conditions (Morais et al., 2023). Additionally, and as far as our understanding goes, there is no information about the comparison of the respective C_D's at the same speed. Our results revealed that the C_{DA} was greater (non-significant) than the C_{DP} but with a strong agreement. One can argue that the main reason for this difference was the FSA. In passive drag, the swimmers are measured in a streamlined position without movement of the propulsive segments. While in active conditions, the motion of the propulsive segments plays a key role. Indeed, it was shown how FSA changes during the stroke cycle and its implications on drag (Gatta et al., 2015; Morais et al., 2020). It seems that this FSA change in active conditions also presents implications on the C_{DA} but with a smaller magnitude than in drag.

Regarding the TDI, our results related to the TDID are within the literature thresholds (D_A was, on average, 1.58 times larger than D_P). On the other hand, based on the respective C_D's, the C_{DA} was on average, 1.25 times larger than C_{DP}. In a study about this topic, the authors reported a TDI value of 1.15 for adult competitive swimmers (Kjendlie and Stallman, 2008). However, the D_A and C_{DA} were measured at maximal speeds and the D_P and C_{DP} were measure at maximal speeds but based on the gliding speed decay. Therefore, one can argue that some differences in speed could be noted. In our study, we calculated both TDI's (drag and C_D's) at the same speed to understand the difference. The significant difference verified in our study between these two TDI's (i.e., based on drag or its respective C_D) may also indicate that the TDI is overestimated when measured with drag rather than with the C_D. This comparison is of particular interest because the C_D is the parameter that better represents the swimmer's hydrodynamic profile (Havriluk, 2007; Morais et al., 2024; Zamparo et al., 2009). Therefore, one can argue that it is also important to compare the C_{DA} against the C_{DP} at the same speed to get deeper insights into the swimmers' hydrodynamics, which ultimately will affect performance.

Although there are no gold standard methods for measuring propulsion, drag, and respective C_D's, those used in the present study are a simple and feasible way to measure these data. Coaches should be aware that the C_D is a "constant" parameter independent of speed and is mainly related to the dimensions of the body (i.e., volume, FSA, etc.) and the shape of the body adopted when moving (i.e., technique), as well as viscosity and the density of water. In this context, by being able to analyze C_D in active and passive situations to compare them without dismissing each one as unnecessary, coaches will obtain much more real data. Consequently, this will allow them to understand whether their swimmers' technique is adequate. Therefore, the interpretation of the effects of C_D's and not just drag, whether passive or active, must be decisive for training guidance, also based on the interpretation of the TDI. As main limitations, it can be considered: (i) the small sample size where only collegiate swimmers were evaluated (despite being proficient swimmers), and; (ii) this comparison was only done at maximal swim speeds. Therefore, future studies should recruit more swimmers of different competitive levels and age groups and at different swim speeds to gather deeper insights about this topic.

Conclusions

This study concludes that proficient swimmers exhibited a higher C_{DA} compared to C_{DP}, with a moderate effect size observed despite the non-significant differences. This discrepancy may be primarily attributed to the significant difference (with a large effect size) in the FSA noted between the active and passive conditions, where FSA was larger in active conditions. Additionally, the TDI, when calculated using the respective C_D's values, was found to be significantly lower compared to the values derived from absolute drag measurements, suggesting that TDI as an indicator of swimming efficiency may be overestimated when based on absolute drag rather than on C_D's.

Acknowledgments

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ORIGINAL SCIENTIFIC PAPER

The Impact of Isometric Exercises on Correcting Upper Body Muscle Imbalances in Young Elite Badminton Players

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Abstract

Overhead athletes are at a higher risk of injury when the internal rotation strength of their dominant shoulder exceeds that of the non-dominant shoulder by 9%, and the external rotation strength is 14% greater in the dominant shoulder compared to the non-dominant shoulder.Though 15% of bilateral strength difference is recognized in the literature as an imbalance. This study examined the effect of isometric exercise on muscle imbalance in young elite badminton players. The study was conducted using an experimental design with pre-test and post-test methodologies. We included approximately 80 Malaysian elite badminton players, comprising 42 male and 38 females, with an average age of 15 years and a maturity level of 2.05 peak height velocity. Participants were randomly assigned to two groups. The experimental group followed a 12-week internal and external rotation isometric exercise regimen. Three key measurements were taken during the study: pre-test data collected before any intervention, post-test1 data after 4 weeks of isometric exercises (12 sessions), and post-test2 data after 12 weeks of isometric exercises (36 sessions). A MicroFET®2 digital handheld dynamometer was used to assess muscle imbalance, focusing on the internal and external rotations of the dominant and non-dominant shoulders. The results showed a significant improvement in the muscle imbalance of the experimental group. Post-tests 1 and 2 revealed considerable improvements in the muscle imbalance ratios ($p<0.01 \eta = 0.791, 0.807$). Isometric exercises were found to significantly influence muscle imbalance ($p<0.01$; $\eta = 0.769$). This study established a positive and significant interaction between isometric exercise repetitions and muscle imbalance within the experimental group. Overall, the findings concluded that isometric exercises can significantly decrease muscle imbalance, with positive and significant effects observed even after just 4 weeks of the intervention in the treatment group.

Keywords: *muscle imbalance; non-dominant shoulder; isometric exercises; genders; maturation*

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Introduction

Despite advancements in sports science, critical gaps persist in understanding how gender-specific training techniques influence intervention program design, particularly in addressing muscle imbalances in overhead athletes (Tatlici et al., 2021). Previous studies have highlighted significant strength imbalances in internal and external shoulder rotation as key risk factors for shoulder injuries (Tülin et al., 2019: Kamalden & Gasibat, 2021). For instance, Stausholm et al. (2021) found that adult badminton players exhibit lower external rotation strength compared to adolescents, suggesting a decline in this strength with age among elite athletes. However, the impact of training techniques tailored to gender remains underexplored.

In one-sided sports such as badminton, squash, and water polo, muscle imbalances are a prevalent concern. Tülin et al. (2019) and Kamalden and Gasibat (2021) have emphasized the need to address these imbalances, yet the application of targeted training methods remains limited. Weakness in the internal and external rotators of the shoulder, particularly in the dominant arm, has been empirically linked to a higher risk of shoulder injuries (Hadzic et al., 2014). Hadzic et al. (2014) demonstrated that an imbalance of 14% greater external rotation strength and 9% greater internal rotation strength in the dominant shoulder compared to the non-dominant shoulder increases injury susceptibility in overhead athletes. Nevertheless, little attention has been given to interventions targeting these specific rotational movements, which are essential for rotator cuff stability.

Existing research, such as Sung et al. (2016) on golfers and Nekooei et al. (2021) on water polo players, has provided sport-specific insights but has largely overlooked generalizable approaches to correcting shoulder muscle imbalances in overhead sports. Furthermore, while isometric exercises are recognized for their safety and efficacy in building strength and reducing pain (Anastasio, 2020), their role in addressing muscle imbalance, biomechanical adaptations, and injury prevention remains poorly understood (Kaldau et al., 2021).

Isometric exercises are widely employed by coaches due to their safety and effectiveness in building muscle strength and reducing pain (Anastasio, 2020). These exercises allow athletes to target specific muscle groups without excessive joint movement, making them particularly suitable for addressing muscle imbalances in overhead athletes. However, their effects on muscle imbalance, biomechanical adaptations, and injury prevention remain poorly understood due to a lack of comprehensive studies (Kaldau et al., 2021). By focusing on isometric internal and external shoulder exercises, this study seeks to explore their potential as a targeted intervention for correcting muscle imbalances, particularly in the non-dominant shoulder, where imbalances are more prevalent.

The duration of a training program can significantly influence its effectiveness in achieving desired outcomes, yet there is limited research on the optimal length of time required to correct muscle imbalances in overhead athletes. This study compares the effects of isometric exercises performed over two different durations (4 weeks) and (12 weeks) to determine the most effective timeline for achieving measurable improvements in strength. Previous studies have shown that measurable improvements in strength and muscle balance can begin as early as (4 weeks) (Anastasio, 2020), while more substantial changes often require (8–12 weeks) of consistent training (Kaldau et al., 2021). By selecting these two durations, the study can compare the short-term and long-term effects of isometric exercises on muscle imbalances. This study aims to address existing gaps by focusing on young, elite badminton players, a group for whom shoulder muscle imbalances remain under-researched. It seeks to evaluate the effectiveness of isometric exercises targeting internal and external shoulder rotations in reducing muscle imbalances, which are critical for injury prevention and optimal performance. Additionally, the study examines the impact of training duration, comparing short-term (4 weeks) and long-term (12 weeks) interventions to determine their effectiveness in improving strength in the non-dominant shoulder. This dual focus aims to provide evidence-based insights for designing tailored training programs for overhead athletes.

Materials and Methods

Research Design

For the present study, which intends to comprehend the cause-and-effect relationships of isometric exercises on the non-dominant shoulder, the current research design is suitable. The dependent variable or variables are measured both before and after the intervention (i.e., the pre-test and post-test) in a pre-test–post-test design (Wang et al., 2020). This entry discusses how the pre-test–post-test design differs from traditional experimental designs, how it is used to evaluate human services and education, potential risks to internal validity, problems with external validity, and strategies for improving the design (Siregar, 2021). In this study, the effects of 36 sessions, three times a week, of internal and external rotation isometric exercises for the non-dominant shoulder (14th week as post-test 1 and 12th week as post-test 2) on the imbalance of shoulder strength in elite badminton players for the experimental group were assessed.

Participants

Based on G*Power calculations, the required sample size for this study was determined to be 28 participants (14 per group), assuming a medium effect size, a significance level (α) of 0.05, and statistical power of 0.80. This sample size was calculated to ensure the robustness of the multivariate analysis, which incorporates seven independent variables, following Cohen's guidelines for statistical power analysis.

Eighty (80) junior elite badminton players (38 females and 42 males) from Kuala Lumpur, Malaysia, participated in this study. The participants were selected based on the following inclusion criteria: (1) being competitive elite players, (2) training regularly and frequently, (3) passing the Physical Activity Readiness Questionnaire (2022 PAR-Q+), and (4) being free of injuries. These criteria were implemented to ensure participant suitability and to minimize dropout rates during the study. Including a larger dataset was aimed at enhancing the statistical power and accuracy of the analysis, reducing the likelihood of errors and increasing the reliability of the results.

Regarding anthropometric data, the participants had an average weight of 51.86±9.07 kg, an average height of 162.54±16.88 cm, and an average body mass index (BMI) of 19.18±2.33 kg/m². The average parental height was recorded as 170.83±5.52 cm (mid-parental height), while the average arm span was 152.37±12.66 cm. The participants' peak height velocity (PHV) was calculated as 2.05±2.10, indicating a mature developmental level. To calculate the PHV and maturity status, the equations proposed by Moore et al. (2015) were

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used, which rely on age and standing height for both sexes. For females, the maturity stage (in years) was calculated using the formula: Maturity stage (years) = −7.709133 + (0.0042232 × [age × height]), and for males, the formula was: Maturity stage (years) = −7.999994 + (0.0036124 × [age × height]). Based on these maturity stage calculations, the maturity status of the participants was classified using the method suggested by Kozieł and Malina (2018). This classification divides participants into three categories: those within −1 to +1 years of PHV were classified as average maturity, those under −1 year of PHV were classified as early maturing, and those over +1 year of PHV were classified as late maturing. This classification helps provide a clearer understanding of the players' developmental stages, which is crucial for interpreting the effects of training and exercise interventions on their physical and athletic performance (refer to Table 1).

Table 1. Descriptive Demographic Characteristics of the Respondent.

Variables		N	f	Mean	SD
Genders	Female	80	38		
	Male		42		
Dominant Hand	Left	80	8		
	Right		72		
Categories	Double	80	21		
	Mixed Double		14		
	Single		45		
Maturity Status	Average	80	30		
	Early		15		
	Late		35		
Age (in Years)	12 years old	80	10	14.74	1.78
	13 years old		9		
	14 years old		10		
	15 years old		12		
	16 years old		18		
	17 years old		21		
Experience (in Years)	5 years	80	19		
	6 years		24		
	7 years		17		
	8 years		14		
	9 years		4		
	10 years		2		
Weight (Kg)		80		51.86	9.07
Height (Cm)		80		162.54	16.88
BMI (Kg/m^2)		80		19.18	2.33
Father Height (Cm)		80		170.83	5.52
Arm Span (Cm)		80		152.37	12.66
Maturity Results		80		2.05	2.10

To make sure there was no bias in the sample selection for the experimental and control groups in this study, the researcher used a random sample approach (on the group selection). As stated by Chua (2011), random sampling, in which each participant has an equal chance of participating, is one kind of probability sampling procedure that is commonly used in evaluations. Participants in the current study were split into two groups: the experimental group and the control group. There were 40 players in total for the experimental group (22 males and 18 females). Temporarily, the control group consisted of 20 male elite badminton players and 20 female badminton players with different levels of maturity.

Furthermore, every participant reported that they work out six times a week. Based in Bukit Kiara, Kuala Lumpur, Malaysia, the Kuala Lumpur Badminton Association is a training facility designed especially for professional badminton players. The players and their parents signed a consent form indicating their consent to participate in the study, which was approved by the University Putra Malaysia Departmental Ethics Committee (REFERENCE NO: JKEUPM-2022-007).

Experiment Procedure

In addition, the researcher gave each participant a detailed explanation of the test protocol, the tools utilized in the investigation, and the benefits and advantages of the study. Beginning with the players' anthropometric data, the study's participants' health and safety were monitored by gathering their responses to a medical history form and the 2022 PAR-Q+ (Nekooei et al., 2019). Every participant signed a consent form, which the researcher collected. During this stage, the pre-test phase of the experiment was initiated by the researcher (Figure 1 shows all stages).

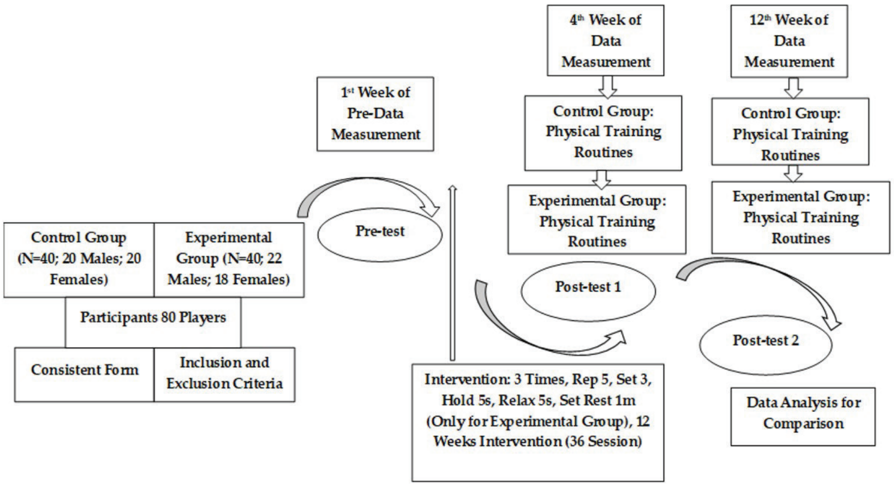

Figure 1. Experimental Procedures.

Both the experimental and control groups continued with individual physical training regimens after completing the pre-test evaluation, as described in Appendix A (https://mjssm.me/clanci/appendices/Gasibat-Appendix.pdf). To be more precise, the experimental group used isometric exercise as an intervention. The researcher made sure that the physical training routines were different from the intervention that the experimental group was doing. The researcher kept a careful eye on both groups and enforced rules throughout the procedure. Additionally, given that a warm-up was conducted before the start of the intervention, the researcher demonstrated to the experimental group the internal and external rotation isometric exercises for the non-dominant shoulder exclusively. These exercises were repeated for the next four weeks following the pre-test.

In this study, participants performed isometric exercises targeting the internal and external rotation of the non-dominant shoulder three times per week. The intervention was divided into two phases. Phase 1 lasted 4 weeks, during which participants completed 12 sessions, followed by the first post-test (Post-Test 1) to assess muscle imbalances between the dominant and non-dominant shoulders and the initial effects of the exercises. Phase 2 extended the intervention for an additional 8 weeks, resulting in a total of 36 sessions over 12 weeks. At the end of this period, the final post-test (Post-Test 2) was conducted to evaluate the long-term effects of the isometric exercises on muscle imbalance and strength in the non-dominant shoulder. Control group participants were also tested at the same time points to compare their results with those of the experimental group. This structured approach provided insights into both the short-term and long-term outcomes of the intervention, with Figure 1 illustrating the entire process.

To track initial development and adaptation, the 4-week evaluation acts as an early checkpoint. This allows for the identification of early increases in muscle strength and the necessary program adaptations (Kloubec, 2010). By giving early feedback, it supports participant motivation and compliance (Shakudo et al., 2011). It also records early physiological changes that are necessary for eventual hypertrophy and strength improvements, such as enhanced motor unit recruitment and coordination (Folland & Williams, 2007).

The 12-week evaluation, which provides a thorough analysis of long-term neural and muscle changes, is the main indicator of the intervention's efficacy (Kraemer et al., 2002). Significant gains in strength and muscle hypertrophy are measured; these improvements usually show up after 8–12 weeks of regular exercise (Ahtiainen et al., 2005). By assessing after 12 weeks, it is ensured that the gains made during the training program are maintained and accurately reflect the program's adaptation (Häkkinen et al., 2000).

Assessment intervals as little as two weeks are too short to detect significant physiological changes or progress. Likewise, it is possible that six weeks will not adequately record notable increases in strength and muscle hypertrophy (Kraemer et al., 2002). As a result, a detailed evaluation of the intervention's influence on strengthening the non-dominant shoulder and preventing muscle imbalance is provided. In summary, a dual-assessment method at 4 and 12 weeks ensures a comprehensive comprehension of both short-term improvement and long-term training consequences.

All participants in the current study were free to carry on with their usual exercise regimens or training activities, and the researcher was not permitted to modify the training program in any way that would impair its synergy. In addition, the researcher gave each participant a detailed explanation of the test protocol, the tools utilized in the investigation, and the benefits and advantages of the study. Over the course of the 12-week intervention program, each participant will have three (3) measurements taken into account. The researcher made certain that the physical training regimens' subject matter was distinct from the intervention that the experimental group undertook.

The researcher kept a careful eye on both groups and enforced rules throughout the procedure. Additionally, the researcher showed the experimental group (but not the control group) how to perform isometric exercises for internal and external rotation on the non-dominant shoulder. To preserve the internal validity of the results, the investigators gave the experimental group exclusive access to single-blinded information on the intervention. Even though everyone trained together, measurements and demonstrations during the ensuing weeks were carried out in a separate location. This strategy made sure the intervention program was only used with the experimental group.

Internal and External Rotation Strength Test

The Digital Handheld Dynamometer (HHD) was selected for its cost-effectiveness, portability, and accuracy, making it a practical tool for measuring muscle strength in training environments (Schrama et al., 2014). In this study, the HHD (MicroFET2, Hoggan Health Industries) was used to assess bilat-

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eral shoulder internal and external rotation strength, with test positions standardized and detailed in Figures 2 and 3. These positions align with validated protocols from prior research (Coinceicao et al., 2018).

The participants warmed up with a warm-up regimen that included two (2) maximal isometric contractions in each direction, followed by a 30-second rest period (Coinceicao et al., 2018). The researcher gave the participants 5 seconds to apply force to the device on the shoulder's internal and external rotations of the affected muscle group before telling them to relax. For every shoulder and rotation (2 × internal rotation and 2 × external rotation in Newton), the maximal isometric strength of both internal and external rotation was measured using two repetitions. There was a 10-second break between each repetition in all tests and a 60-second break between strength testing (Coinceicao et al., 2018). The participants were vocally motivated by the tester during the force generation phase. The maximum value recorded from the two repetitions of each test session was used for analysis (Coinceicao et al., 2018). Muscle balance was assessed using the External Rotation/Internal Rotation Ratios (ER/IR X 100%) (Stausholm et al., 2021). The researcher ran every test to gather pre-test data on the first testing day. The pre-test, which is planned to happen early in the intervention program week, comprised measurements of the internal and exterior rotation, as described below. At the training location, the exams were held in the evening. The study's post-test was identical to the pre-test, with the same warm-up protocols and testing techniques. Post-tests were given to the participants on the final day of week four for (post-test 1) and twelve for (post-test 2).

Intervention Programme (Experimental Group)

Isometric exercises for the non-dominant shoulder for 12 weeks Maximum Voluntary Contraction: 70–80% (MVC). (see Table 2)

Figure 2. Shoulder External Rotation Measurement

Figure 3. Shoulder Internal Rotation Measurement

Table 2. Isometric Shoulder External and Internal Rotation Exercises.

Exercise	How to perform
Isometric Shoulder External Rotation (Figure 4)	The shoulder on which you are exercising should be closest to the wall. Bend your elbow 90 degrees, make a fist, and press the back of your hand into the wall as if you were rotating your arm outwards. Repeat 5 times, hold 5 s, relax 5 s, 3 sets, rest 1 m between sets, 3 times a week.
Isometric Shoulder Internal Rotation (Figure 5)	Position your body so that you are facing a door frame or an outside corner of a wall. The shoulder on which you are exercising should be near the door opening or corner. Bend your elbow 90 degrees, make a fist, and gently press into the corner wall or door jamb as if you were trying to rotate your hand inward towards your belly button. Repeat 5 times, hold 5 s, relax 5 s, 3 sets, rest 1 m between sets, 3 times a week.

Figure 4. Isometric Shoulder External Rotation

Figure 5. Isometric Shoulder Internal Rotation

Data Analysis

Two-way repeated measures ANOVA was employed to evaluate the effects of two independent variables training duration (4 vs. 12 weeks) and group (intervention vs. control) on dependent variables such as shoulder rotation strength and muscle imbalance. This method allowed for the assessment of within-subject effects (changes over time) and between-group differences while accounting for interaction effects between the two factors (Aljandali, 2017; Tabachnick et al., 2013). The analysis provided a robust framework for examining the influence of isometric training duration on key outcomes while controlling for individual variability.

Results

Two-way repeated-measures ANOVA was used to analyze continuous outcome variables in the presence of one or more independent factors to achieve the stated goal. The mean value of isometric exercises for muscle imbalance for both the experimental and control groups throughout the course of the 12-week intervention is displayed in the descriptive statistic (see Table 3). For example, there was a 28% difference in the pre-test mean value of isometric exercises for muscle imbalance between the experimental group (96.39±0.86 and 68.33±10.46). Additionally, there was a 17% difference in the mean value of isometric exercises for muscle imbalance for post-test 1 (96.39±0.86 and 79.28±5.88), and a 3% rapid decline in the mean value of isometric exercises for muscle imbalance for post- test 2 (96.39±0.86 and 93.51±1.68). According to descriptive statistics, there was a progressive trend towards muscle imbalance during isometric exercises in the mean value of the exercises.

Table 3. Descriptive Analysis of Isometric Exercises on Muscle Imbalance between Experimental and Control Group.

Variables		Mean	SD	N
	Experimental Group	96.39	0.86	40
PREDER/IR	Control Group	96.37	0.95	40
	Total	96.39	0.88	80
	Experimental Group	68.33	10.46	40
PRENDER/IR	Control Group	58.71	10.63	40
	Total	65.68	11.32	80
	Experimental Group	96.39	0.86	40
POST1DER/IR	Control Group	95.45	1.77	40
	Total	96.13	1.25	80
	Experimental Group	79.28	5.88	40
POST1NDER/IR	Control Group	67.29	11.54	40
	Total	75.98	9.47	80
	Experimental Group	96.39	0.86	40
POST2DER/IR	Control Group	96.38	0.92	40
	Total	96.39	0.87	80
	Experimental Group	93.51	1.68	40
POST2NDER/IR	Control Group	67.47	11.81	40
	Total	86.34	13.26	80

PREDER\IR= Pre-Test Dominant Ratio; POST1DER/IR= Post-Test 1 Dominant Ratio; POST2DER/IR= Post-Test 2 Dominant Ratio; PRENDER\IR= Pre-Test Non-Dominant Ratio; POST1NDER/IR= Post-Test 1 Non-Dominant Ratio; POST2NDER/IR= Post-Test 2 Non-Dominant Ratio

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The control group's pre-test mean value of muscle imbalance was found to differ by 37.7% between 96.37±0.95 and 58.71±10.63. Additionally, the average muscle imbalance values for post-test 1 and post-test 2 were 95.45±1.77 and 67.29±11.54, respectively, differing by 28.2% and 28.9%, respectively. According to descriptive statistics, there was no progression between post-test 1 and post-test 2, but there was a slight progressive trend towards muscle imbalance in the mean value of the muscle imbalance between the pre-test and post-test 1. For the control group, the mean value of muscle imbalance varied between 28.2% and 37.7% overall.

In this investigation, the association between isometric exercise and muscle imbalance during post-tests 1 and 2 was investigated using a two-way repeated-measures ANOVA. Muscle imbalance factors had the biggest influence on the model (Ƞ= 0.903), as shown in Table 4, and were significantly influenced with time (p=0.000). Additionally, the model parameters (refer to Table 4) show that post-tests 1 and 2 positively affect muscle imbalance (p=0.000; Ƞ=0.791). In conclusion, players' muscle imbalance ratios reduced over time (p=0.000; Ƞ= 0.807). As a result, the experimental group's muscle imbalance ratios also improved.

Table 4. Analysis of Two-Way ANOVA Repeated Measurement Effect of 4th and 12th Weeks on Isometric Exercises towards Muscle Imbalance.

Effect	Testing	Value	F	p	Partial Eta Squared
Muscle Imbalance	Wilks' Lambda	0.097[a]	998.381[b]	0.000	0.903
Post-test 1 vs Post-test 2		0.209[a]	200.914[b]	0.000	0.791
Muscle Imbalance * Post-test 1 vs Post-test 2		0.193[a]	221.544[b]	0.000	0.807

a. Design: Intercept + GROUP; Within Subjects Design: Muscle Imbalance + Post-Test 1 vs Post-Test 2 + Muscle Imbalance * Post-Test 1 vs Post-Test 2; b. Exact Statistic

The relationship between isometric exercise and muscle imbalance during post-test 1 and post-test 2 was investigated in this study using a two-way repeated measures ANOVA. As demonstrated by the within-subject effects tests following the sphericity assumption (refer to Table 5), the isometric exercise variables had a significant impact on muscle imbalance (p= 0.000; Ƞ= 0.762) and repetitions (or measurements) (p= 0.000; Ƞ= 0.903). Table 5 shows that there is a significant effect of isometric exercises on muscle imbalance (p= 0.000; Ƞ= 0.769).

Table 5. Test of Within-Subject Effects Test.

Effects		Mean Square	F	p	Partial Eta Squared
Muscle Imbalance	Sphericity Assumed	73888.301	998.381	0.000	0.903
Post-test 1 vs Post-test 2		3141.411	342.837	0.000	0.762
Muscle Imbalance * Post-test 1 vs Post-test 2		3172.993	355.975	0.000	0.769

The experimental group and the control group in Table 6 and Figure 6 demonstrate between subjects' effects; nonetheless, it is seen that both groups exhibit a substantial effect on the intervention with 43.4% (p=0.000; Ƞ =0.434). For a short time, the effects of isometric exercises (post-test 1 and post-test 2) on muscle imbalance were demonstrated by the tests on the between-subject effects and the pairwise comparison test (p=0.000). As a result, in the experimental group as opposed to the control group, there is a positive and significant interaction between the number of repetitions of isometric exercises and muscle imbalance (p=0.000).

Table 6. Test of Between-Subjects Effects (Experimental group vs Control Group).

Source	Mean Square	F	p	Partial Eta Squared
Intercept	3711093.754	35579.98	0.000	0.997
Group	8570.695	82.171	0.000	0.434
Error	104.303			

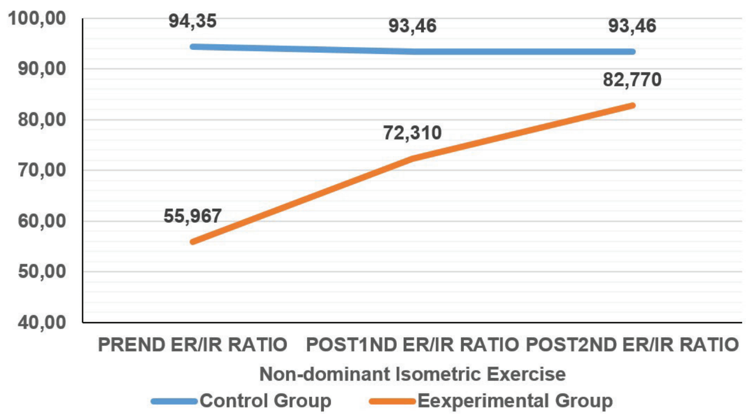

Figure 6. Marginal Mean Different for Non-dominant Shoulder.

Table 7. Multiple Pairwise Comparisons of Muscle Imbalance and Post-test 1 vs Post-test 2.

Muscle Imbalance	Muscle Imbalance	Mean Difference	p
Experimental group	Control Group	23.799*	0.000
Pre-Test vs Post-Test 1		-4.650*	0.000
Post-Test 1 vs Post-Test 2		-3.836*	0.000
Pre-Test vs Post-Test 2		-8.486*	0.000

Another way to put it is that as soon as the isometric exercises begin, and even up to four weeks later, they have a good and significant effect on the treatment group. Specifics of the results are shown in Table 7.

Discussion

This study shows that isometric exercises effectively reduce shoulder muscle imbalances in young elite badminton players, especially when performed over longer intervention durations. Athletes' ability to maintain muscle strength and balance is significantly impacted by isometric exercises and their length, as shown by statistical analysis. But timing and duration of exercise are also very important in helping athletes avoid abrupt, unforeseen injuries. This is mostly due to the development of muscle flexibility, which restores the chronically restricted equilibrium that can be brought about by things like fatigue, injuries, bad posture, or exercise habits (Du & Fan, 2023; Cools et al., 2014).

A two-way ANOVA with repeated measures was used to examine the connection between isometric exercises and muscle imbalance during the pre-test, post-test 1, and post-test 2 in this study. Time was found to have a considerable impact on the variables related to muscle imbalance in the study, with the model showing the most impact. Additionally, post-tests 1 and 2 had a positive impact on muscle imbalance. In conclusion, athletes' muscle imbalance lessened with time. As a result, participating in the experimental group enhances muscle balance. These results support the idea that specific isometric training can help elite badminton players' non-dominant shoulder muscles become more balanced. This is a significant discovery because it implies that professional badminton players may benefit from these exercises in terms of injury prevention and performance enhancement.

Although our results show that isometric exercises are beneficial, earlier studies such as Malliou et al. (2004) found that movements have shown to be beneficial for treating muscle imbalance in the rotator cuff muscle group, include pull-ups, lat pull-downs, push-ups, overhead presses, and reverse pull-ups. On the other hand, the intervention strategy differs noticeably. Unlike previous research that predominantly advocated intervention targeting the non-dominant side, the Malliou study included exercises for both the dominant and non-dominant shoulders (Kamalden & Gasibat, 2021; Tülin et al., 2019).

While Sung et al. (2016) focused primarily on exercises directly related to golf-specific motions, their findings on the benefits of core and non-dominant arm strength training offer parallels to our study's emphasis on the importance of targeted interventions for muscle balance. However, their work neglected to address fundamental movements, such as shoulder internal and external rotation, which are essential for overhead sports like badminton and golf. As demonstrated by Pennock et al. (2018), Hams et al. (2019), and Hadzic et al. (2014), deficits in shoulder internal and external rotation strength significantly increase the risk of injury and compromise rotator cuff support.

Hadzic et al. (2014) found that a 14% imbalance in external rotation strength between shoulders and a 9% difference in internal rotation strength in dominant versus non-dominant shoulders were strongly associated with higher injury risks in overhead athletes. These findings are consistent with our study, which demonstrates that isometric exercises significantly reduce shoulder muscle imbalances in young elite badminton players. Our study aligns particularly well with Rio et al. (2015), who highlighted the importance of isometric exercises in treating tendinopathy, noting their ability to reduce pain and enhance functionality. Moreover, Kinsella et al. (2017) underscored that isometric exercises outperform isotonic exercises (eccentric and concentric) in improving muscle performance, a finding that reinforces our approach to addressing muscle imbalances.

Additionally, our study supports Tiwari et al. (2011), who emphasized the importance of prolonged training duration for improving agility, balance, and muscle dexterity in badminton players. We observed that longer intervention durations with isometric exercises produced more pronounced reductions in shoulder muscle imbalances, highlighting the critical role of consistent, sustained training programs in preventing injuries and enhancing performance.

These consistencies underscore the efficacy of isometric exercises, particularly when applied with longer intervention durations, in addressing muscle imbalances and supporting young elite athletes in overhead sports.Sung et al. (2016), who emphasized isotonic training, provided useful insights into strength improvement; however, our findings distinctly highlight the specific benefits of isometric exercises in enhancing rotator cuff strength and addressing asymmetries. This distinction is further supported by Brumitt and Dale (2009), who observed that professional badminton players benefited from isometric exercises by increasing tendon stiffness and reducing injury risk. These observations align with our emphasis on consistency and structured, long-term training, which proved effective in significantly reducing shoulder muscle imbalances in young elite badminton players.

Parle et al. (2017) illustrated the potential of progressively lengthening isometric training sessions for managing and preventing injuries, particularly in patients with rotator cuff tendinopathy. This finding parallels our results, which demonstrate that extended durations of isometric training interventions contribute to greater reductions in shoulder imbalances and injury prevention. Similarly, Gerstner et al. (2022) and Sumartiningsih (2021) emphasized the long-term benefits of isometric training, showing improvements in muscle endurance and metabolic capacity. These studies resonate with our findings, reinforcing the importance of sustained isometric exercise programs in promoting functional strength and balance.

Lum and Barbosa (2019) highlighted the relevance of isometric movements for persistent muscle activation, particularly in physical therapy and endurance sports. This underscores the broader applicability of our findings, as isometric exercises not only address muscle imbalances but also enhance rehabilitation efforts and reduce injury risks, making them an essential component of training regimens for athletes, especially those in overhead sports like badminton.

The practice of executing one to three sets of 5 to 10 repetitions of isometric contractions that last at least 5 seconds, as explained by Izraelski (2012) reaffirms the significance of prolonged timing and consistency in triggering muscle activity and building strength. The present study, in conjunction with other research findings, indicates that a clear consensus cannot be reached regarding the ideal duration for maintaining isometric exercises aimed at strengthening muscle imbalance. Nonetheless, it has been observed that greater consistency in these exercises is associated with increased physical agility or flexibility in individuals (Blomstrand et al., 2017). A review by Malliaras et al. (2015) on isometric exercises also recommended longer, more repetitive routine sessions in order to improve muscle tenacity and balance compared to participants who performed the same exercises for shorter amounts of time.

The individual context and goals of the training or rehabilitation program determine how long isometric exercises should last (Lim & Wong, 2018). Sports warm-up programs frequently include short isometric exercises to improve muscle strength and power, while longer-duration exercises are better for injury recovery and tasks requiring extended muscle engagement (Clifford et al., 2020). Our study examined the effects of 4-week and 12-week isometric exercises on shoulder muscle imbalance in young, professional badminton players. These ranges of time enable a thorough investigation of the ways in which exercise length affects the mitigation of muscle imbalance and improvement of shoulder stability (Clifford et al., 2020). This methodology is consistent with the concept that the length of exercise needs to be tailored to the unique requirements of the target group and the intended results (Birrer & Morgan, 2010).

The importance of length on the intervention outcomes was also taken into consideration in the results of the descriptive analysis (Table 4). This showed how to overcome muscle barriers and improve strength and ability through position-specific training techniques, which improves performance and endurance in the field. These outcomes supported the conclusions made by Bolotin and Bakayev (2016), who suggested that elite athletes perform isometric exercises with a focus on injury prevention.

As a result, our research adds to the increasing amount of data demonstrating the value of isometric exercises, particularly when it comes to treating muscle imbalance in the non-dominant shoulder. The present study's methodology is consistent with earlier research conducted by Malliou et al. (2004) and Kinsella et al. (2017); however, the disparity in intervention approaches and the necessity of taking into account fundamental movements in overhead sports, as suggested by some scholars such as Sung et al. (2016) and Hadzic et al. (2014), highlighted the significance of a customized and all-encompassing exercise regimen to optimize athletic performance and minimize the risk of injury. Our study's results are consistent with those of several other studies, such as Tiwari et al. (2011) and Parle et al. (2017). They demonstrated the value of extended duration, regularity, and isometric exercise in enhancing muscle strength, agility, balance, and preventing injuries in athletes and people undergoing rehabilitation.

These results underscore the need for coaches and trainers to incorporate structured, long-term isometric training into strength and conditioning programs for young athletes. Such programs can enhance shoulder stability, reduce muscle imbalances, and mitigate injury risks. For optimal outcomes, training plans should prioritize progressive overload and consistency, tailoring exercise duration to the specific performance or rehabilitation goals of the athlete.

Limitations and strengths

Research constraints refer to deficiencies or inadequacies in the study that might not always support the results of richer data. In this situation, future research must address a few shortcomings of the study, despite the significant benefits it has produced. First, only junior elite badminton players classified by Swann et al. (2015). as competitive-elite athletes were included in this study. The study's conclusions might therefore be applied to badminton players at different skill levels.

Second, due to psychophysiological factors related to human performance that are outside the researcher's control, there may be situations during the intensive intervention method where the participants provide performances inconsistently. Nonetheless, players are strongly urged to give them all during the data collection procedure. Because human interaction is always subject to changes based on preferences and the chance that they will give the study their all, these limitations are evident. The conditions and circumstances that may affect or limit the research data methodologies and analysis are indicated in the restrictions. The constraints in this study were unpredictable.

As previous academic studies have shown, physical activity or fitness levels in the non-dominant body side have not been measured or included very often because of the belief that their effects on interventions are restricted. Sung et al. (2016) conducted research that demonstrated this disregard, as they rarely evaluated or tested these variables. Prior studies have mostly examined the effectiveness of isometric exercise therapies for body part movement, gender, maturation stage, and other related characteristics. As a result, following the example given by Sung et al. (2016), the current study does not identify physical activity as a variable of interest.

Thus, in order to help elite badminton players, enhance and develop their performance and efficiency in the sphere of sports, the current study has been able to shed light on the relationship between isometric exercises, shoulder strength, and muscle imbalance. This study highlights the importance of isometric exercises in preventing elite athletes from experiencing previously unheard-of injuries during training, enhancing their performance, and above all improving their natural ability to move while also building their physical strength and endurance.

For athletes, muscle balance and agility are critical, and hundreds of sports agencies use this study as a guide. With the use of this study information, organizations will be able to reassess and introspect their current training regimen and adjust their tactics as necessary to ensure that athletes receive the greatest possible training and performance. Consequently, it is important to note that a thorough knowledge and comprehension of the isometric exercises' relationship to shoulder muscle strength would benefit millions of athletes worldwide by enabling them to assess the type of exercises they are performing and create the most effective training plan for improving muscle balance and flexibility. Even though the study's goal has been achieved, more thorough research procedures are needed to incorporate various badminton involvement levels. This would make the results more broadly applicable, which might result in more harmoniously important contributions to the discipline.

Conclusions

Isometric exercises significantly reduce muscle imbalance, with the experimental group showing statistically significant improvements in muscle balance between dominant and non-dominant shoulders across pre-test, post-test 1, and post-test 2. Trainers should prioritize longer intervention durations, such as twelve-week sessions, to promote sustained endurance and metabolic adaptations, while shorter durations, such as four weeks, may focus on immediate strength and power gains. Recommendations should align exercise duration with specific training or rehabilitation goals for optimal outcomes.

Informed Consent Statement

Written consent was obtained from parents of all subjects involved in the study.

Data Availability Statement

Data are available upon reasonable request.

Appendix A

Physical training routines for badminton (https://mjssm.me/clanci/appendices/Gasibat-Appendix.pdf

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DOI 10.26773/mjssm.250310

Guidelines for Authors

Revised Maj 2021

*** Please use the bookmark function to navigate within the guidelines. ***

When preparing the final version of the manuscripts, either NEW or REVISED authors should strictly follow the guidelines. Manuscripts departing substantially from the guidelines will be returned to the authors for revision or, rejected.

1. UNIFORM REQUIREMENTS

1.1. Overview

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There is no charge for submissions and no page charge for accepted manuscripts. However, if the manuscript contains graphics in color, note that printing in color is charged.

MJSSM adopts a double-blind approach for peer reviewing in which the reviewer's name is always concealed from the submitting authors as well as the author(s)'s name from the selected reviewers.

MJSSM honors a six-weeks for an initial decision of manuscript submission.

Authors should submit the manuscripts as one Microsoft Word (.doc) file.

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Format the manuscript in A4 paper size; margins are 1 inch or 2.5 cm all around. Type the whole manuscript double-spaced, justified alignment.

Use Times New Roman font, size eleven (11) point.

Number (Arabic numerals) the pages consecutively (centering at the bottom of each page), beginning with the title page as page 1 and ending with the Figure legend page.

Include line numbers (continuous) for the convenience of the reviewers.

Apart from chapter headings and sub-headings avoid any kind of formatting in the main text of the manuscripts.

1.2. Type & Length

MJSSM publishes following types of papers:

Original scientific papers are the results of empirically- or theoretically-based scientific research, which employ scientific methods, and which report experimental or observational aspects of sports science and medicine, such as all clinical aspects of exercise, health, and sport; exercise physiology and biophysical investigation of sports performance; sport biomechanics; sports nutrition; rehabilitation, physiotherapy; sports psychology; sport pedagogy, sport history, sport philosophy, sport sociology, sport management; and all aspects of scientific support of the sports coaches from the natural, social and humanistic side. Descriptive analyses or data inferences should include rigorous methodological structure as well as sound theory. Your manuscript should include the following sections: Introduction, Methods, Results, and Discussion.

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Original scientific papers should be:

- Up to 3000 words (excluding title, abstract, tables/figures, figure legends, Acknowledgements, Conflict of Interest, and References);
- A structured abstract of less than 250 words;
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Review papers should provide concise in-depth reviews of both established and new areas, based on a critical examination of the literature, analyzing the various approaches to a specific topic in all aspects of sports science and medicine, such as all clinical aspects of exercise, health, and sport; exercise physiology and biophysical investigation of sports performance; sport biomechanics; sports nutrition; rehabilitation, physiotherapy; sports psychology; sport pedagogy, sport history, sport philosophy, sport sociology, sport management; and all aspects of scientific support of the sports coaches from the natural, social and humanistic side.

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Editorials are written or commissioned by the editors, but suggestions for possible topics and authors are welcome. It could be peer reviewed by two reviewers who may be external or by the Editorial Board.

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Short reports of experimental work, new methods, or a preliminary report can be accepted as two page papers. Your manuscript should include the following sections: Introduction, Methods, Results, and Discussion.

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Invited papers and award papers include invited papers from authors with outstanding scientific credentials. Nomination of invited authors is at the discretion of the MJSSM editorial board. MJSSM also publishes award papers selected by the scientific committee of the MSA annual conference.

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- Maximum number of references is 30;
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Transfer of Learning on a Spatial Memory Task between the Blind and Sighted People Spatial Memory among Blind and Sighted

Original Scientific Paper

Transfer of learning on a spatial memory task

Selcuk Akpinar[1], Stevo Popović[1,2], Sadettin Kirazci[1]

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E-mail: stevop@ac.me

Word count: 2,980

Abstract word count: 236

Number of Tables: 3

Number of Figures: 3

2.1.1. Title

Title should be short and informative and the recommended length is no more than 20 words. The title should be in Title Case, written in uppercase and lowercase letters (initial uppercase for all words except articles, conjunctions, short prepositions no longer than four letters etc.) so that first letters of the words in the title are capitalized. Exceptions are words like: "and", "or", "between" etc. The word following a colon (:) or a hyphen (-) in the title is always capitalized.

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Affiliation consists of the name of an institution, department, city, country/territory(in this order) to which the author(s) belong and to which the presented / submitted work should be attributed. List all affiliations (each in a separate line) in the order corresponding to the list of authors. Affiliations must be written in English, so carefully check the official English translation of the names of institutions and departments.

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If an author belongs to more than one institution, all corresponding superscript digits, separated with a comma with no space in between, should be present behind the family name of this author.

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Whenever possible expand your authors' affiliations with departments, or some other, specific and lower levels of organization.

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Corresponding author's name with full postal address in English and e-mail address should appear, after the affiliations. It is preferred that submitted address is institutional and not private. Corresponding author's name should include only initials of the first and middle names separated by a full stop (and a space) and the last name. Postal address should be written in the following line in sentence case. Parts of the address should be separated by a comma instead of a line break. E-mail (if possible) should be placed in the line following the postal address. Author should clearly state whether or not the e- mail should be published.

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All authors are required to provide word count (excluding title page, abstract, tables/figures, figure legends, Acknowledgements, Conflict of Interest, and References), the Abstract word count, the number of Tables, and the number of Figures.

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The second page of the manuscripts should be the abstract and key words. It should be placed on second page of the manuscripts after the standard title written in upper and lower case letters, bold.

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Results of the analysis of…
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- ✓ **Methods**

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- ✓ *Table position of the research football team*

2.3.2 Ethics

When reporting experiments on human subjects, there must be a declaration of Ethics compliance. Inclusion of a statement such as follow in Methods section will be understood by the Editor as authors' affirmation of compliance: "This study was approved in advance by [name of committee and/or its institutional sponsor]. Each participant voluntarily provided written informed consent before participating." Authors that fail to submit an Ethics statement will be asked to resubmit the manuscripts, which may delay publication.

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All contributors who do not meet the criteria for authorship should be listed in the 'Acknowledgements' section. If applicable, in 'Conflict of Interest' section, authors must clearly disclose any grants, financial or material supports, or any sort of technical assistances from an institution, organization, group or an individual that might be perceived as leading to a conflict of interest.

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References should be placed on a new page after the standard title written in upper and lower case letters, bold.

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One work by one author

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- ✓ In the study by Reilly (1997), soccer players…
- ✓ In 1997, Reilly's study of soccer players…

Works by two authors

- ✓ Duffield and Marino (2007) studied…
- ✓ In one study (Duffield & Marino, 2007), soccer players…
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2.4.3. Examples for Reference list

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Borg, G. (1998). *Borg's perceived exertion and pain scales*: Human Kinetics.

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Duffield, R., & Marino, F. E. (2007). *Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions. European Journal of Applied Physiology, 100*(6), 727–735. https://doi.org/10.1007/s00421-007-0468-x

Works by three to twenty authors
Nepocatych, S., Balilionis, G., & O'Neal, E. K. (2017). Analysis of dietary intake and body composition of female athletes over a competitive season. *Montenegrin Journal of Sports Science and Medicine, 6*(2), 57–65. https://doi.org/10.26773/mjssm.2017.09.008

Works by more than twenty authors
Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A.,… Bangsbo, J. (2003). The yo-yo intermittent recovery test: physiological response, reliability, and validity. *Medicine & Science in Sports & Exercise, 35*(4), 697–705. https://doi.org/10.1249/01.mss.0000058441.94520.32

Works by group of authors
NCD-RisC. (2017). Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128.9 million children, adolescents, and adults. *Lancet*, 390(10113), 2627-2642. https://doi.org/10.1016/s0140-6736(17)32129-3

Works by unknown authors
Merriam-Webster's collegiate dictionary (11th ed.). (2003). Merriam-Webster.

Journal article (print)
Scruton, R. (1996). The eclipse of listening. *The New Criterion, 15*(3), 5–13.

Journal article (electronic)
Aarnivala, H., Pokka, T., Soininen, R., Mottonen, M., Harila-Saari, A., & Niinimaki, R. (2020). Trends in age- and sex-adjusted body mass index and the prevalence of malnutrition in children with cancer over 42 months after diagnosis: a single-center cohort study. *European Journal of Pediatrics,* 179(1), 91-98. https://doi.org/10.1007/s00431-019-03482-w

Thesis and dissertation
Pyun, D. Y. (2006). *The proposed model of attitude toward advertising through sport*. [Unpublished Doctoral Dissertation]. The Florida State University.

Book
Borg, G. (1998). *Borg's perceived exertion and pain scales*: Human Kinetics.

Chapter of a book
Armstrong, D. (2019). Malory and character. In M. G. Leitch & C. J. Rushton (Eds.), *A new companion to Malory* (pp. 144-163). D. S. Brewer.

Reference to a Facebook profile
Little River Canyon National Preserve (n.d.). *Home* [Facebook page]. Facebook. Retrieved January 12, 2020 from https://www.facebook.com/lirinps/

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All tables should be included in the main manuscript file, each on a separate page right after the Reference section.

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Number (Arabic) tables consecutively in the order of their first citation in the text.

Tables and table headings should be completely intelligible without reference to the text. Give each column a short or abbreviated heading. Authors should place explanatory matter in footnotes, not in the heading. All abbreviations appearing in a table and not considered standard must be explained in a footnote of that table. Avoid any shading or coloring in your tables and be sure that each table is cited in the text.

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Table heading should be written above the table, in Title Case, and without a full stop at the end of the heading. Do not use suffix letters (e.g., Table 1a, 1b, 1c); instead, combine the related tables. *See* example:

- ✓ **Table 1.** Repeated Sprint Time Following Ingestion of Carbohydrate-Electrolyte Beverage

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All text appearing in tables should be written beginning only with first letter of the first word in all capitals, i.e., all words for variable names, column headings etc. in tables should start with the first letter in all capitals. Avoid any formatting (e.g., bold, italic, underline) in tables.

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Table footnotes should be written below the table.

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- ✓ *Note.* CI: confidence interval; Con: control group; CE: carbohydrate-electrolyte group.

Specific notes explain, qualify or provide information about a particular column, row, or individual entry. To indicate specific notes, use superscript lowercase letters (e.g. $^{a, b, c}$), and order the superscripts from left to right, top to bottom. Each table's first footnote must be the superscript ^{a}.

- ✓ ^{a}One participant was diagnosed with heat illness and n = 19.^{b}n =20.

Probability notes provide the reader with the results of the texts for statistical significance. Probability notes must be indicated with consecutive use of the following symbols: * † ‡ § ¶ || etc.

- ✓ *P<0.05,†p<0.01.

2.5.4. Table citation

In the text, tables should be cited as full words. *See* example:

- ✓ Table 1 (first letter in all capitals and no full stop)
- ✓ ...as shown in Tables 1 and 3. (citing more tables at once)
- ✓ ...result has shown (Tables 1-3) that... (citing more tables at once)
- ✓ ....in our results (Tables 1, 2 and 5)... (citing more tables at once)

2.6. Figures

On the last separate page of the main manuscript file, authors should place the legends of all the figures submitted separately.

All graphic materials should be of sufficient quality for print with a minimum resolution of 600 dpi. MJSSM prefers TIFF, EPS and PNG formats.

If a figure has been published previously, acknowledge the original source and submit a written permission from the copyright holder to reproduce the material. Permission is required irrespective of authorship or publisher except for documents in the public domain. If photographs of people are used, either the subjects must not be identifiable or their pictures must be accompanied by written permission to use the photograph whenever possible permission for publication should be obtained.
Figures and figure legends should be completely intelligible without reference to the text.

The price of printing in color is 50 EUR per page as printed in an issue of MJSSM.

2.6.1. Figure legends

Figures should not contain footnotes. All information, including explanations of abbreviations must be present in figure legends. Figure legends should be written bellow the figure, in sentence case. *See* example:

- ✓ **Figure 1.** Changes in accuracy of instep football kick measured before and after fatigued. SR – resting state, SF – state of fatigue, *p>0.01, †p>0.05.

2.6.2. Figure citation

All graphic materials should be referred to as Figures in the text. Figures are cited in the text as full words. *See* example:

- ✓ Figure 1
- × figure 1
- × Figure 1.
- ✓ ….exhibit greater variance than the year before (Figure 2). Therefore…
- ✓ ….as shown in Figures 1 and 3. (citing more figures at once)
- ✓ ….result has shown (Figures 1-3) that... (citing more figures at once)
- ✓ ….in our results (Figures 1, 2 and 5)... (citing more figures at once)

2.6.3. Sub-figures

If there is a figure divided in several sub-figures, each sub-figure should be marked with a small letter, starting with a, b, c etc. The letter should be marked for each subfigure in a logical and consistent way. *See* example:

- ✓ Figure 1a
- ✓ …in Figures 1a and b we can…
- ✓ …data represent (Figures 1a-d)…

2.7. Scientific Terminology

All units of measures should conform to the International System of Units (SI).

Measurements of length, height, weight, and volume should be reported in metric units (meter, kilogram, or liter) or their decimal multiples.

Decimal places in English language are separated with a full stop and not with a comma. Thousands are separated with a comma.

Percentage	Degrees	All other units of measure	Ratios	Decimal numbers
✓ 10%	✓ 10º	✓ 10 kg	✓ 12:2	✓ 0.056
× 10 %	× 10 º	× 10kg	× 12 : 2	× .056

Signs should be placed immediately preceding the relevant number.		
✓ 45±3.4	✓ p<0.01	✓ males >30 years of age
× 45 ± 3.4	× p < 0.01	× males > 30 years of age

2.8. Latin Names

Latin names of species, families etc. should be written in italics (even in titles). If you mention Latin names in your abstract they should be written in non-italic since the rest of the text in abstract is in italic. The first time the name of a species appears in the text both genus and species must be present; later on in the text it is possible to use genus abbreviations. *See* example:

- ✓ First time appearing: *musculus biceps brachii*
- ✓ Abbreviated: *m. biceps brachii*

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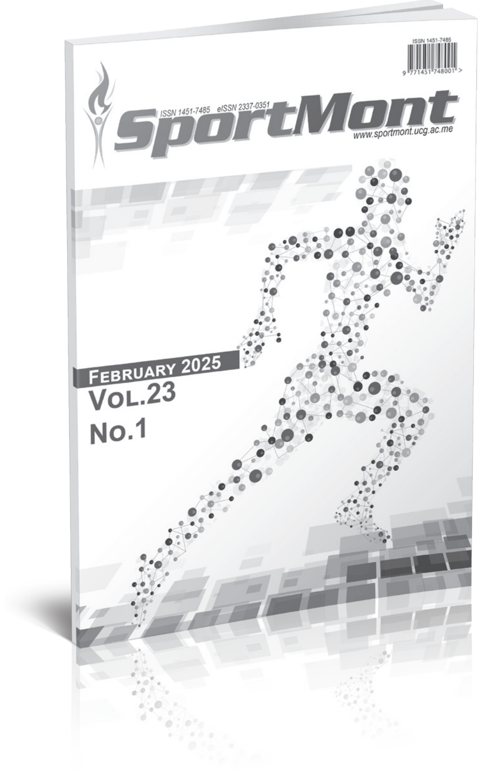

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SMJ is published three times a year, in February, June and October of each year. SMJ publishes original scientific papers, review papers, editorials, short reports, peer review - fair review, as well as invited papers and award papers in the fields of Sports Science and Medicine, as well as it can function as an open discussion forum on significant issues of current interest.

SMJ covers all aspects of sports science and medicine; all clinical aspects of exercise, health, and sport; exercise physiology and biophysical investigation of sports performance; sport biomechanics; sports nutrition; rehabilitation, physiotherapy; sports psychology; sport pedagogy, sport history, sport philosophy, sport sociology, sport management; and all aspects of scientific support of the sports coaches from the natural, social and humanistic side.

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MONTENEGRIN SPORTS ACADEMY

Founded in 2003 in Podgorica (Montenegro), the Montenegrin Sports Academy (MSA) is a sports scientific society dedicated to the collection, generation and dissemination of scientific knowledge at the Montenegrin level and beyond.

The Montenegrin Sports Academy (MSA) is the leading association of sports scientists at the Montenegrin level, which maintains extensive co-operation with the corresponding associations from abroad. The purpose of the MSA is the promotion of science and research, with special attention to sports science across Montenegro and beyond. Its topics include motivation, attitudes, values and responses, adaptation, performance and health aspects of people engaged in physical activity and the relation of physical activity and lifestyle to health, prevention and aging. These topics are investigated on an interdisciplinary basis and they bring together scientists from all areas of sports science, such as adapted physical activity, biochemistry, biomechanics, chronic disease and exercise, coaching and performance, doping, education, engineering and technology, environmental physiology, ethics, exercise and health, exercise, lifestyle and fitness, gender in sports, growth and development, human performance and aging, management and sports law, molecular biology and genetics, motor control and learning, muscle mechanics and neuromuscular control, muscle metabolism and hemodynamics, nutrition and exercise, overtraining, physiology, physiotherapy, rehabilitation, sports history, sports medicine, sports pedagogy, sports philosophy, sports psychology, sports sociology, training and testing.

The MSA is a non-profit organization. It supports Montenegrin institutions, such as the Ministry of Education and Sports, the Ministry of Science and the Montenegrin Olympic Committee, by offering scientific advice and assistance for carrying out coordinated national and European research projects defined by these bodies. In addition, the MSA serves as the most important Montenegrin and regional network of sports scientists from all relevant subdisciplines.

The main scientific event organized by the Montenegrin Sports Academy (MSA) is the annual conference held in the first week of April.

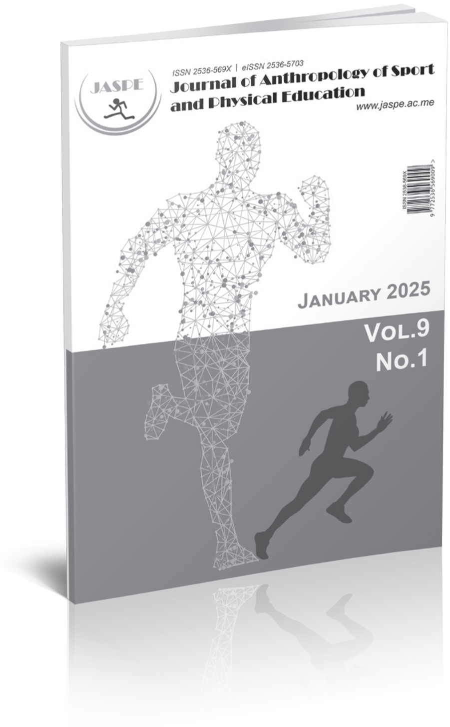
Annual conferences have been organized since the inauguration of the MSA in 2003. Today the MSA conference ranks among the leading sports scientific congresses in the Western Balkans. The conference comprises a range of invited lecturers, oral and poster presentations from multi- and mono-disciplinary areas, as well as various types of workshops. The MSA conference is attended by national, regional and international sports scientists with academic careers. The MSA conference now welcomes up to 200 participants from all over the world.

It is our great pleasure to announce the upcoming 22th Annual Scientific Conference of Montenegrin Sports Academy "Sport, Physical Activity and Health: Contemporary Perspectives" to be held in Dubrovnik, Croatia, from 3 to 6 April, 2025. It is planned to be once again organized by the Montenegrin Sports Academy, in cooperation with the Faculty of Sport and Physical Education, University of Montenegro and other international partner institutions (specified in the partner section).

The conference is focused on very current topics from all areas of sports science and sports medicine including physiology and sports medicine, social sciences and humanities, biomechanics and neuromuscular (see Abstract Submission page for more information).

We do believe that the topics offered to our conference participants will serve as a useful forum for the presentation of the latest research, as well as both for the theoretical and applied insight into the field of sports science and sports medicine disciplines.

Journal of Anthropology of Sport and Physical Education



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- Open-access and freely accessible online;
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- Community-based dialogue on articles;
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JASPE is published four times a year, in January, April, July and October of each year. JASPE publishes original scientific papers, review papers, editorials, short reports, peer review - fair review, as well as invited papers and award papers in the fields of Anthropology of Sport and Physical Education, as well as it can function as an open discussion forum on significant issues of current interest.

JASPE covers all aspects of anthropology of sport and physical education from five major fields of anthropology: cultural, global, biological, linguistic and medical.

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