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The Development and Validity of Inertial Measurement Unit System for Tracking Wheelchair Kinematics (IMU-Tennis)

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ABSTRACT

Vorapojpisut S, Subtaweewasin W, Chokchaisiri C, Anektanarojkul S, Kaijindaporn V, Sukthai T, Hayashi S, Jampangam B, Saadprai S. The Development and Validity of Inertial Measurement Unit System for Tracking Wheelchair Kinematics (IMU-Tennis). An IMU system was developed to track wheelchair tennis kinematics in both competitive and training sessions, gathering data to analyze and enhance athletes' skills and fitness. The purpose of this study is to validate the developed of an IMU System (IMU-Tennis) against the Two-Dimensional Motion Analysis (2DMA). Thirty (N = 30) healthy male and female participants 18 to 30 years of age underwent 4 skill-related wheelchair fitness tests: (a) One Stroke Push Test (OSPT) for distance (m); (b) Muscle Power Sprint Test (MPST) for velocity (m/s); (c) 10x5 Meter Sprint Test (10x5MST); and (d) Slalom Test (ST) for time (sec). The %Error for OSPT, MPST, 10x5MST, and ST was 0.06, 0.54, 0.00, and 0.04, respectively, using the Paired T-Test that showed no significant differences between the methods ($P = 0.101$, $P = 0.081$, $P = 0.880$, and $P = 0.316$). The Pearson Correlation Coefficient indicated high correlations ($r = 1.000$, $r = 0.997$, $r = 1.000$, and $r = 1.000$). Compared to the 2DMA, the development of the IMU system demonstrates high validity in distance, velocity, and time, thus making it an effective tool for tracking wheelchair tennis kinematics.

Key Words: Inertial Measurement Unit, Kinematics, Motion Analysis, Wheelchair Tennis

INTRODUCTION

At the Tokyo 2020 Paralympic Games, 554 athletes with disabilities used wheelchairs to compete in 4 sports (9). Among the wheelchair sports, wheelchair tennis, wheelchair rugby, and wheelchair basketball are particularly popular and are characterized by high-intensity, intermittent efforts in which athletes must move continuously across the court (5). Accordingly, the analysis of wheelchair kinematics is crucial, because such data provide coaches with objective information on the athletes' physical demands and performance that allows for a more precise optimization and individualization of training and competition (7,19,21).

In current practice, wheelchair sport coaches rely primarily on video recordings of training sessions and competitive matches, combined with subjective observational notes. This approach does not allow for comprehensive tracking of the athletes' movements, especially when multiple athletes are present, as is common in team or group training. This results in the detailed and simultaneous tracking of incomplete and discontinuous movements of multiple athletes (2,9,22).

Two-dimensional motion analysis (2DMA) software offers a more quantitative option, but it has several well-established limitations. First, the 2DMA cannot capture the depth (z-axis) of movement, which restricts analysis to a planar view and prevents a full three-dimensional kinematic assessment or real-time kinetic analysis (14,17,26). Second, its accuracy is highly dependent on camera placement and field-of-view that can lead to blind spots when athletes move outside the camera coverage or when they are occluded by other players or equipment (17,20,25). Third, accurate analysis often requires multiple camera angles and, in some systems, motion capture markers are placed on the athletes that increase set-up time and reduces practicality for routine use in real training and competition environments (1,16,31).

Laboratory-based three-dimensional motion capture systems can provide more detailed kinematic and kinetic data, but they are typically very expensive and require a complex infrastructure. Hence, they are not easily deployed in on-court settings (11,28). In addition, many wheelchair tennis programs and national teams, particularly in low- and middle-income settings cannot afford laboratory-based motion capture systems (1,3,13,23, 28). A lower-cost, portable alternative is crucial to enable broader adoption of objective kinematic monitoring in real-world practice. Therefore, there is a need for practical, sport-specific tools that allow coaches in wheelchair sports to obtain valid on-court kinematic data with minimal disruption to training and/or competition.

Given these limitations in wheelchair tennis, we aimed to develop a dedicated device that enables coaches to collect kinematic information during both training and competition. Specifically, the system was designed to quantify parameters such as distance covered, time and velocity. When combined with fitness testing and other performance assessments, these data can be used to evaluate an athlete's physical profile in terms of strength, power, speed, agility, and related attributes with the ultimate goal of supporting safe performance development and reducing the risk of injury. Additionally, information obtained from training and matches can be used to design individualized, evidence-based training programs for wheelchair tennis athletes.

Therefore, we developed an inertial measurement unit (IMU)-based system for monitoring and tracking wheelchair kinematics during on-court activities. The system was designed to be user-friendly and practical for both coaches and athletes, thereby offering a feasible solution to several of the limitations associated with video-based and 2D motion analysis approaches. We

hypothesized that the development of the IMU system (IMU-Tennis) will demonstrate good criterion validity and strong correlations with 2DMA for estimates of distance travelled, velocity, and time.

The Developed IMU System for Tracking Wheelchair Tennis Kinematics (IMU-Tennis)

The proposed system consists of a wireless IMU sensor unit based on the M5StickC board and a laptop computer running a custom graphical user interface (GUI). As illustrated in Figure 1, the M5StickC was mounted on the left side of the wheel axle. The wheel axle was chosen as the mounting location because placing the sensor on the wheel rim would increase the influence of centrifugal forces during propulsion, which could distort the resultant forces derived from thrust and gravity and lead to inaccurate distance estimation during the thrust phase.

The M5StickC is a compact Internet of Things (IoT) development board that incorporates an ESP32 microcontroller, enabling wireless communication via Wi-Fi and Bluetooth. It includes a 0.96-inch TFT LCD display and an internal battery that, in its standard configuration, provides approximately 1 hour of operation. In the present study, the M5StickC was integrated with an MPU-6886 IMU module and an external 5000 mAh power supply, which extended continuous monitoring capability to approximately 48 hours. This extended battery life is sufficient to cover multiple training sessions and match-play periods within the same day without recharging, which enhances the practical applicability of the system in real-world wheelchair tennis environments. Data were transmitted at a sampling frequency of 100 Hz via Bluetooth within a range of up to 30 m. This sampling rate is sufficient to capture the rapid changes in wheelchair kinematics during high-intensity wheelchair tennis movements and to support near real-time analysis over prolonged training and competition periods.



Figure 1. The M5StickC Board.

The MPU-6886 (Figure 2) is a 6-axis inertial sensor comprising a 3-axis linear accelerometer and a 3-axis gyroscope. It outputs 16-bit digital signals and can measure linear acceleration within ranges of ± 2 , ± 4 , ± 8 , and ± 16 g, as well as angular velocity within ranges of ± 250 , ± 500 , ± 1000 , and ± 2000 °/sec. These specifications allow the system to capture both translational and rotational components of wheelchair motion with sufficient resolution for kinematic analysis.

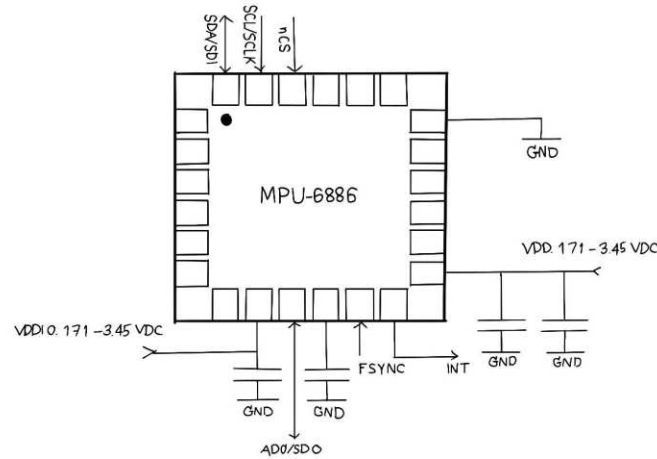


Figure 2. The IMU Model MPU-6886.

Firmware for the M5StickC board was developed in the C programming language using Visual Studio Code with the PlatformIO extension. We implemented the FreeRTOS real-time operating system and adopted a multithreaded architecture (Figure 3). This approach allowed the microcontroller to handle multiple tasks concurrently, such as data acquisition from the IMU, wireless data transmission, and updating the on-board display, thereby reducing delays associated with sequential processing. The task scheduling mechanism of FreeRTOS allocated these subtasks to different threads of the processing unit that improved the overall efficiency and responsiveness of the system, which is an important requirement for real-time applications involving continuous data streaming.

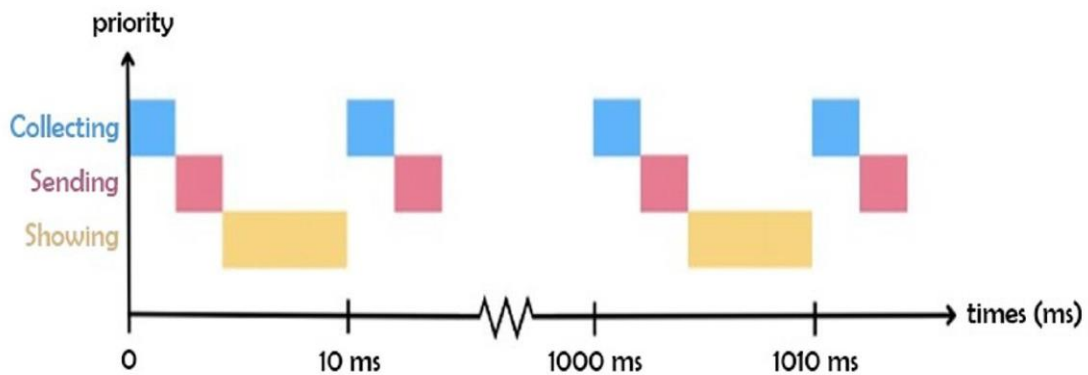


Figure 3. The Multithreading Model.

For IMU-Tennis's Graphical User Interface (GUI) development, we used PyQt, a Python-based library for creating cross-platform graphical interfaces. The GUI application received data transmitted from the M5StickC via Bluetooth, displayed the processed kinematic results, and exported the data to Microsoft Excel files using the openpyxl library. The athletes' demographic

and health-related information were stored alongside test results, enabling longitudinal tracking and subsequent retrieval for further analysis or monitoring.

The GUI was specifically designed to allow coaches to review wheelchair kinematics during and after testing in a format that is intuitive and practical for applied use. For the future, the analysis software is implemented in Python and, upon publication of this work, we intend to make the core processing scripts and a compiled application available to the wheelchair tennis research community for non-commercial research use. This will facilitate replication, secondary analyses, and future extensions of the system in different wheelchair sport settings.

The Developed IMU-Tennis Design

The overall system architecture for wheelchair tennis coaches is presented in Figure 4. The M5StickC board was installed on the left wheel of the wheelchair, and IMU data were wirelessly transmitted via Bluetooth to a laptop computer, where the GUI displayed the kinematic information in real time for coaching purposes.



Figure 4. The System Design for Wheelchair Tennis Coaches.

For motion detection, the IMU-Tennis measured linear acceleration along the x-, y-, and z-axes, depending on the direction of movement. During wheelchair propulsion, periodic changes in the direction of the gravity vector relative to the sensor were captured by the accelerometer. These changes were used to detect wheel rotations and to compute the corresponding angular displacement. Relying on the accelerometer for this purpose allowed us to avoid integration drift associated with low angular velocities when using gyroscope signals alone. In slow rotational movements, gyroscope-based distance estimation can be substantially affected by noise and by error accumulation over time when integrating angular velocity to derive angular displacement. By contrast, detecting changes in the gravity vector from accelerometer data provides a more stable basis for estimating the number of wheel rotations and, consequently, the linear distance travelled.

For data processing, IMU-Tennis output was converted to travelling distance using a multi-step procedure. First, the atan2 function from the NumPy library was applied to determine the instantaneous angle of the wheel based on the measured acceleration components (Equation [eq1]). Second, linear distance was calculated by multiplying the angular displacement by the

wheel radius (Equation [eq2]). Third, velocity was derived as the first derivative of distance with respect to time (Equation [eq3]). Representative time-series examples of acceleration, distance, and velocity are presented in Figure 5 ([fig:5a]) - 5 ([fig:5c]), respectively. Therefore, before each data collection session, the GUI prompts the user to enter basic information, namely the radius of the wheel to be analyzed, the weight of the wheelchair, and the body weight of the wheelchair user, so that these inputs can be incorporated into the calculations to improve the accuracy of the kinematic parameters of interest.

$$\text{Angle } (\theta) = \left(\frac{\text{Linear acceleration along the } x\text{-axis}}{\text{Linear acceleration along the } y\text{-axis}} \right) \quad \text{eq1}$$

$$\text{Linear Distance } (s) = \text{Angle } (\theta) \times \text{Wheel Radius } (r) \quad \text{eq2}$$

$$\text{Velocity } (v) = \frac{d}{dt} (\text{Linear Distance } (s)) \quad \text{eq3}$$

The data were sampled at 100 Hz and transmitted via Bluetooth. In a purely sequential programming scheme, processing these high-frequency data while simultaneously updating the display could lead to delays and potential data loss. To mitigate this issue, we employed a multithreading strategy under FreeRTOS. Multithreading enabled the system to separate data reception, processing, and plotting tasks into parallel threads, thereby maintaining real-time performance and minimizing latency in the visualized outputs.

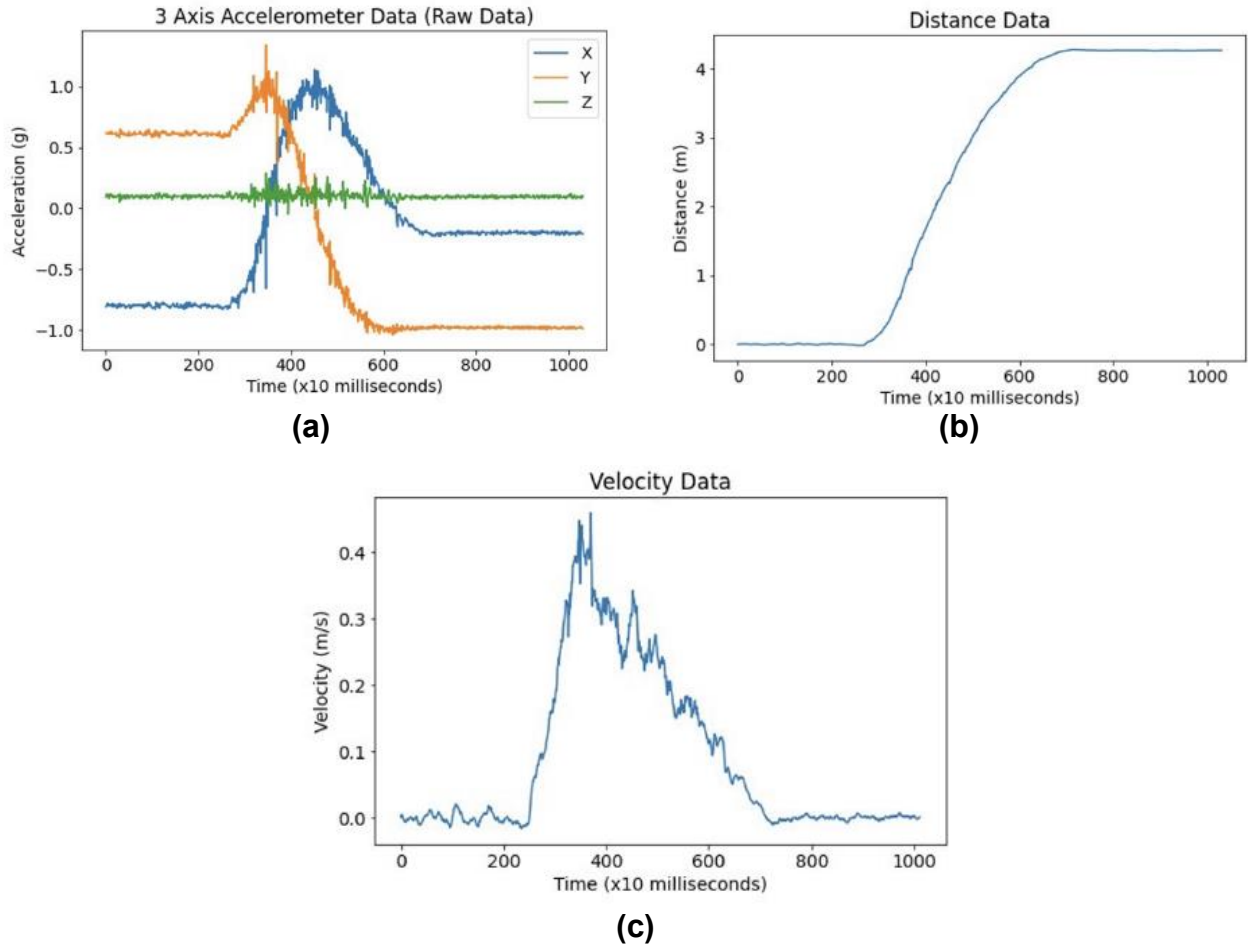


Figure 5. (a) Samples of Wheelchair Traveling Acceleration Data. (b) Samples of Wheelchair Traveling Distance Data. (c) Samples of Wheelchair Traveling Velocity Data.

The GUI was organized into 3 main components. First, the Wheelchair Tennis Athlete Information Interface (Figure 6) allowed coaches to record and review athletes' personal and health information, which was stored in Excel format together with test identifiers and dates. Second, the IMU-Tennis Control Interface (Figure 7) provided controls for system operation, including selection of test modes (e.g., One Stroke Push Test, Muscle Power Sprint Test, and Manual Mode), initiation and termination of data collection (Start/Stop), and management of the serial connection with the Bluetooth device. Third, the Test Results Interface (Figure 8) displayed key outcome variables such as distance travelled, time, average velocity, and power estimates. This interface allowed coaches to inspect results immediately after a trial and to compare performance across different tests and sessions.

Application

Info

ข้อมูลของผู้ใช้เก้าอี้รถเข็น

ชื่อ-นามสกุล

ผู้ประเมิน

วันเดือนปีเกิด

ส่วนสูง (cm.)

น้ำหนักเก้าอี้รถเข็น (kg.)

หมายเลข HN

โรคประจำตัว

อายุ (ปี)

เพศ

ช่าย

น้ำหนักผู้ใช้ (kg.)

BMI (กก./ม.²)

Confirm

Figure 6. The Wheelchair Tennis Athlete Information Interface

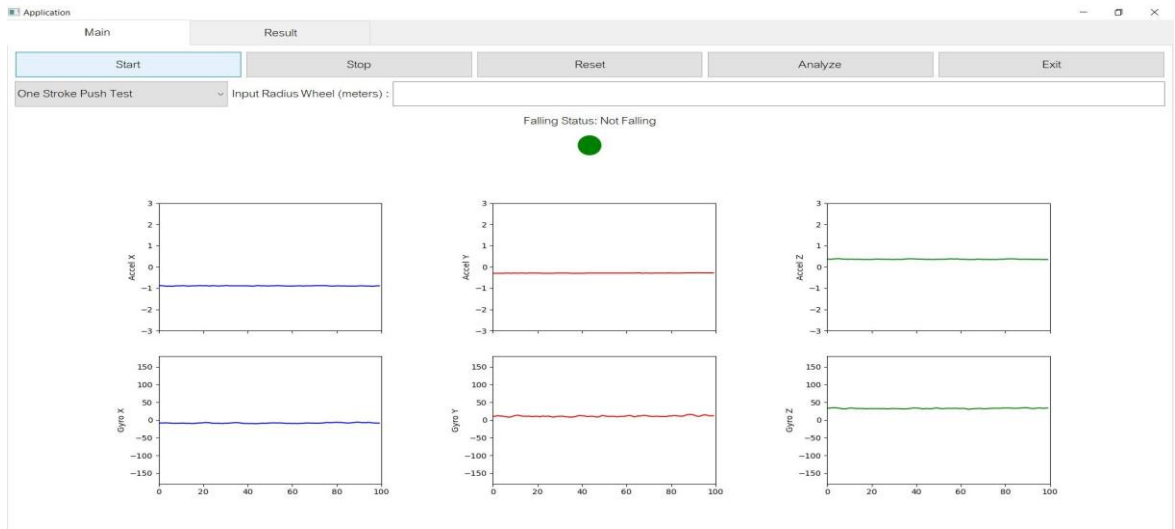


Figure 7. The IMU-Tennis Control Interface.

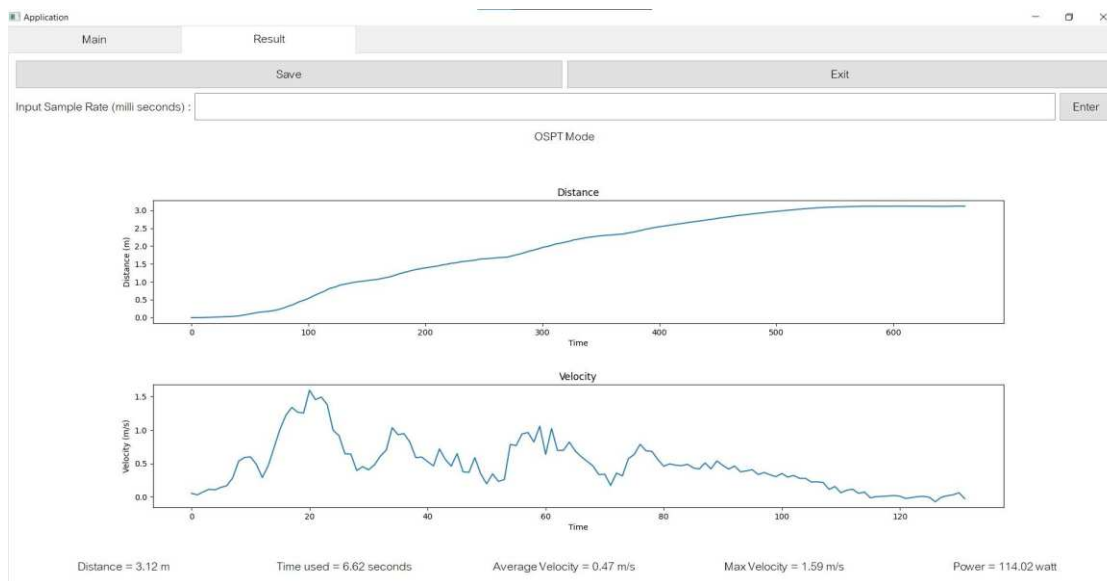


Figure 8. The Test Results Interface

The objective of this study is to develop and validate an inertial measurement unit system for tracking wheelchair kinematics (IMU-Tennis).

METHODS

Subjects

The Inclusion Criteria of this research are as follows: (a) male and female participants 18 to 30 years of age; (b) participants must be healthy with no history of congenital disease; and (c) have a body mass index of 18.50 to 24.90 kg/m². On the other hand, the Exclusion Criteria are as follows: (a) if participants are unable to complete 100% of the experiment; (b) suffer an injury to the muscular system or the nervous system, participation would be immediately terminated; (c) if participants are unable to strictly observe and follow the experiment procedures; and (d) if they wish to leave the experiment, their participation would be immediately terminated.

The sample size was calculated using the G*Power program, with the effect size $dz=0.80$. The researchers used the large effect size estimation method for the testing of the difference between 2 means (8). The significant level (α err prob) was set at 0.05, and the power value ($1-\beta$ err prob) was set at 0.95. The calculated sample size was 23 participants with a margin for dropout of 25%. Therefore, the researchers conducted this study with 30 participants.

In addition to fundamental kinematic variables (i.e., distance, time, and instantaneous velocity), various derived performance indices specifically designed for the requirements of wheelchair tennis were calculated. All indicators were produced automatically by the analysis program and exported with the raw kinematic data for subsequent statistical analysis.

The study was approved by the Human Research Ethics Committee of Thammasat University (Science) (Certificate of Approval No. 071/2566). The researchers confirm that all the methods were performed in accordance with the relevant guidelines and regulations. All the participants read and signed the consent form before participating in the study.

Procedures

The participants who met the Inclusion Criteria were asked to complete the (Physical Activity Readiness Questionnaire Plus: PAR-Q+2019) and the personal information questionnaire. Then, the participants were assigned with identification numbers and their resting heart rate was measured.

The researchers prepared the testing ground by installing a set of Sony Cyber-shot DSC-WX800 camcorder on tripods, which were set at the height of 30 centimeters above the ground to capture the motion of the whole body of the participants and located at a distance of 12 meters from the center of each test. In addition, the sampling rate of the camcorder data and the sensor output was identically set at 100Hz, as depicted in Figure 9.

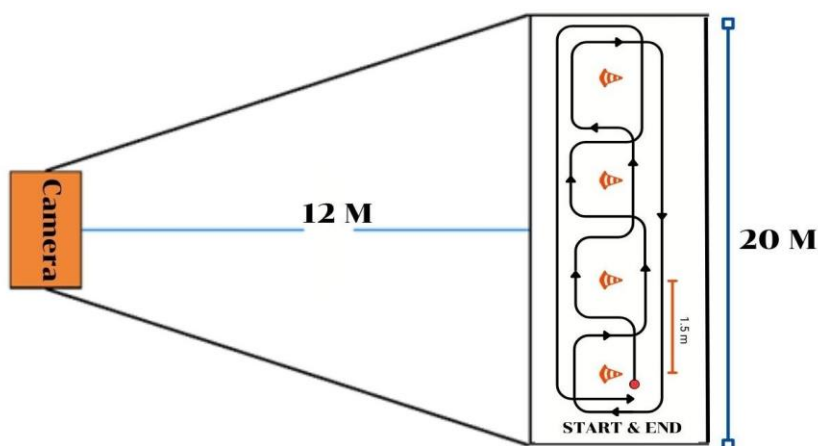


Figure 9. The Installation of the Video Camera.

After the installation of the camcorder was complete, the participants were instructed to spend 10 minutes to warm up and familiarize themselves with the wheelchair. The wheelchair used for this research was the MATSUNAGA model A-MAX/MP-ADJUST. This model of wheelchair is capable of adjusting its width and height to suit the participant's physiology and, therefore, can support users of different physiologies. The width of the wheelchair was adjusted to support the participants' hips perfectly (i.e., not too narrow or too wide). The height of the chair was also adjusted so that the participants' knees were perpendicular to the ground as they rested their feet on the footrest. Then, the participants were instructed to sit comfortably with their backs against the backrest.

Then, the researchers explained the procedures and demonstrated how to perform the 4 skill-related wheelchair fitness tests for wheelchair users, which are: (a) the One Stroke Push Test (OSPT); (b) the Muscle Power Sprint Test (MPST); (c) the 10x5 Meter Sprint Test (10x5MST); and (d) the Slalom Test (ST), respectively.

When the demonstration was complete, the participants started with 1 practice session to familiarize themselves with the movements of the 4 skill-related wheelchair fitness tests. Then, they were asked to perform each test twice while the researchers recorded their movement data using the camcorder to verify that they had performed the tests accordingly.

After the 4 skill-related wheelchair fitness tests were complete, the researchers analyzed the camcorder data using the Kinovea program (version 0.9.5) and exported the IMU-Tennis data output into a Microsoft Excel table (the data were collected since the movement of the

wheelchair have started), in order to compare the data of the 2 methods. In this regard, the sampling rate of the camcorder and the IMU-Tennis was set at 100Hz throughout the research.

At the end of the first time of each test, the participants were instructed to take a 5-minute break. They were instructed to take a 10-minute break at the end of each test session, or until their heart rate returned to resting state and express a fatigue rating of 11 or lower during the rest period, the researchers would measure the participant's heart rate while asking them questions about their perceived level of Rating of Perceived Exertion with a fatigue rating of Borg's scale 6-20 (Ritchie, 2012). After the participants completed all the test sessions, the researchers instructed them to perform the cool-down.

Skill-Related Wheelchair Tennis Fitness Tests

The researchers used the 4 skill-related wheelchair tennis fitness tests, which were adapted from "Validity and Reliability of Skill-Related Fitness Tests for Wheelchair-Using Youth with Spina Bifida" (6) for measuring the traveling distance, velocity, and time data. These tests focus on strength, power, speed and agility that closely match the situations the wheelchair tennis athletes face during training and competitions.

OSPT: A strength test that measures the distance traveled from a single maximal wheelchair push in a straight line, as illustrated in Figure 10.

MPST: A power and speed test that measures the time required to propel the wheelchair as fast as possible over a distance of 15 meters, as illustrated in Figure 11.

10×5MST: A speed and strength test that measures the time required to propel the wheelchair back and forth as fast as possible, 10 times between 2 cones placed 5 meters apart, as illustrated in Figure 12.

ST: An agility test that measures the time required to maneuver the wheelchair around 4 cones placed 1.5 meters apart, as illustrated in Figure 13.

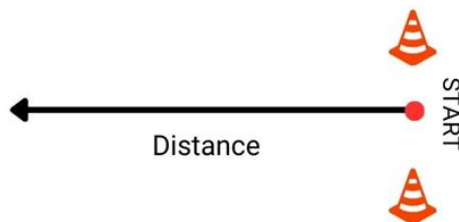


Figure 10. The One Stroke Push Test (OSPT).

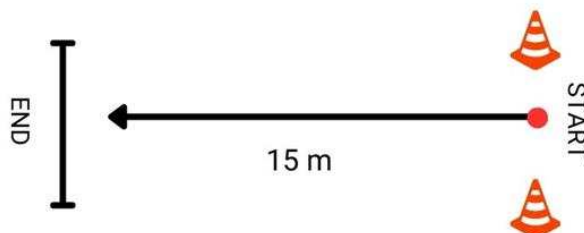


Figure 11. The Muscle Power Sprint Test (MPST).

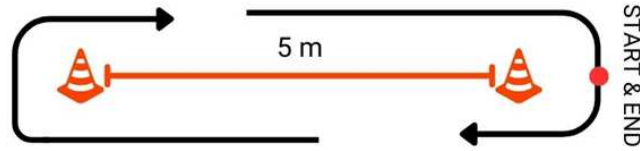


Figure 12. The 10 x 5 Meter Sprint Test (10 x 5MST).

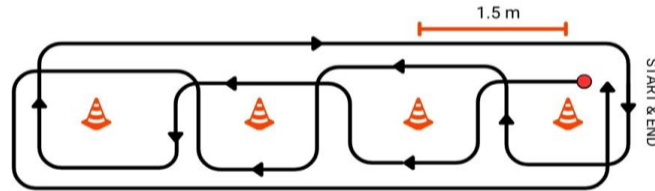


Figure 13. The Slalom Test (ST).

Statistical Analyses

In order to determine the validation of the kinematic data, the researchers used the results of traveling distance, speed, and time of the 4 skill-related wheelchair fitness tests from the 2 actual testing sessions to calculate the mean of each testing session of all the participants. Then, the researchers compared the resulting data gained from the IMU-Tennis and the 2DMA. The researchers calculated the %Error using the Equation ([eq4]). If the statistical error is less than 5 percent (10), that means the measurement error of IMU-Tennis was acceptable, in comparison to the standardized 2DMA.

$$\%Error = \frac{|2DMA\ value - IMU\ System\ value|}{2DMA\ value} \times 100 \quad eq4$$

The researchers tested the distribution of the data, using the Kolmogorov-Smirnov statistic. If the data distribution was normal, the researchers would then use the Paired Samples T-Test statistic. On the other hand, if the data distribution was abnormal, the researchers would use the Wilcoxon Sign Rank Test statistic. The validity of the result was confirmed with the statistical significance of $P < 0.05$, 2-tailed. The researchers also used the Pearson Correlation Coefficient statistic to study the correlation between the data from the IMU system and the 2DMA, with a statistical significance level of $P < 0.01$. In this regard, the correlation of both the devices was considered to be 'low' if the correlation coefficient was in the range of 0.00–0.50; and to be 'moderate', 'good', and 'high' if the correlation coefficient was in the range of 0.50–0.74, 0.75–0.90, and 0.90–1.00, respectively.

RESULTS

A total of 30 participants joined this research. Among those participants, there were 14 male and 16 female participants. The average age was 20.47 ± 1.43 years (range: 18 to 23 years).

The average weight was 61.70 ± 9.47 kg (range: 48 to 77 kg). The average height was 168.03 ± 8.59 cm (range: 155 to 185 cm), and the average BMI was 21.74 ± 2.31 kg/m² (range: 18.82 to 25.33 kg/m²).

According to the output data from the 4 skill-related wheelchair fitness tests, the researchers found that all measurements of the developed IMU-Tennis were less than 5 percent different from the measurements of the 2DMA. This result showed that the developed IMU system caused an acceptable level of error, in terms of the traveling distance, speed, and time. In addition, no difference of statistical significance was found in the wheelchair sports kinematic data measured from the tests. On the contrary, the measurements of the wheelchair sports kinematic data showed a high correlation between both methods. Hence, it is safe to assume that the developed IMU system was valid enough to be used for tracking the wheelchair tennis, which are high-movement activities while the players are required to constantly move around the field all the time, in comparison to the use of the 2DMA, as depicted in Table 1.

Table 1. Mean, Standard Deviation, Percentage Error, and Statistical Results for Both Methods Across the Four Skill-Related Wheelchair Fitness Tests (N = 30).

Skill-Related Fitness Test	Measurement Method	Mean $\pm$ SD	% Error	P Value (Paired t-Test)	r Value (Pearson Correlation)
OSPT (m)	IMU-Tennis	9.03 ± 2.50	0.06	0.101	1.000*
	2DMA	9.02 ± 2.50			
MPST (m/sec)	IMU-Tennis	1.66 ± 0.33	0.54	0.081	0.997*
	2DMA	1.66 ± 0.32			
10 x 5MST (sec)	IMU-Tennis	151.75 ± 22.84	0.00	0.880	1.000*
	2DMA	151.76 ± 22.88			
ST (sec)	IMU-Tennis	42.59 ± 7.71	0.04	0.316	1.000*
	2DMA	42.60 ± 7.71			

*Correlation is significant at the 0.01 level (two-tailed). **Difference is significant at $P < 0.05$ (two-tailed).

DISCUSSION

According to the result of this study, in terms of the traveling distance measurement results between the IMU-Tennis and the 2DMA, the level of correlation of results from these two measurement methods was quite excellent. This finding is in line with a research study on the subject of “Real-Life Wheelchair Mobility Metrics from IMUs”. In that study, the researchers used the IMU and the 2DMA to measure several mobility metrics of people with disabilities, namely, the distance, linear velocity of the wheelchair, number of pushes, duration of pushes, number of turns, magnitude of turns, and inclination. The results of that study showed an

excellent level of correlation of the distance measurement results between the developed IMU and the 2DMA with a correlation coefficient of 1.00 (30).

Additionally, according to the result of this study, the researchers also found that the distance measurement results, which were measured during the OSPT test and with the IMU-Tennis and the 2DMA, represented a %Error of 0.06. This finding is in line with a research study, on the subject of “A Novel AHRS Inertial Sensor-Based Algorithm for Wheelchair Propulsion Performance Analysis”, in which they studied the reliability of IMU sensors by collecting the kinematic motion data from the IMU sensors through the test, namely, pushing the wheelchair back and forth over a distance of 14 meters for 5 times; and compared the results of the IMU sensor system against the results acquired from the Jenoptik LDM301, a laser-based distance measuring device. They found that the %Error was 2.21, which showed that the IMU sensor system that was based on a study and development of an IMU sensor, also was highly valid for tracking the traveling distance of the wheelchair (24).

On the other hand, in terms of the velocity measurement results, which were measured during the MPST test and with the IMU-Tennis and the 2DMA, the level of correlation of results from these two methods was quite excellent. This finding is in line with a research study, on the subject of “Validation of Inertial Measurement Units for Tracking 100 m Sprint Data”, which studied the validation of the IMU used for measuring the velocity of athletes during the 100-meter dash. In that study, the researchers measured and compared the peak velocity of the IMU against the result from the LAVEG Sport, a laser-based distance-measuring method. They found that the correlation coefficient of the velocity measured by the two methods was quite excellent ($r = 0.92$) (18).

In terms of the traveling time measurement results, which were measured during the 10x5MST and ST with the IMU system and the 2DMA, the level of correlation of results from these two methods was quite excellent. This finding is in line with a research study on the subject of “Development and Validation of a Physical Activity Monitor for Use on a Wheelchair”, in which the researchers developed an IMU for the purpose of monitoring physical activities of wheelchair users. The researchers specifically aimed to measure the traveling time of participants with spinal cord injuries and compared the results from the IMU against the results of the 2DMA. They also found that the correlation efficient of the results measured by the two methods was quite excellent ($ICC(2,1) > 0.981$) (7).

Moreover, the findings of this research study are in line with a research study, on the subject of “Wheel Skid Correction is a Prerequisite to Reliably Measure Wheelchair Sports Kinematics Based on Inertial Sensors”, in which the researchers studied the incidents of wheel slippage during the wheelchair basketball competition. The researchers instructed the participants to perform a variety of tests, including the Straight 5m sprint test, the ST, and the U-turn (left & right) test. In that study, they used a IMU sensor system that they developed to gather the data, including the traveling distance, the velocity, the rotational speed, the degree of rotation, and compared the results against the data collected with the 3-dimensional motion analysis (3DMA) software (Optitrack). They found that the correlation coefficient of the results measured by the two methods was quite excellent ($ICC = 0.917 - 1.000$) as well (29).

Compared with other validated inertial measurement units (IMUs) widely used in sports science and rehabilitation, such as the ActiGraph GT9X, Xsens MVN, and Noraxon MyoMotion systems, the performance of IMU Tennis appears similar in terms of the correlation coefficients reported for key movement variables. In previous work, studies employing ActiGraph and Xsens have generally shown validity coefficients in the range of 0.90–0.99 for metrics such as

distance, speed, and duration when these devices were evaluated against laboratory reference methods during controlled wheelchair locomotion protocols (12,15,32).

Although some commercially available IMU systems provide extended functionality, such as multi-segment kinematic analysis or built-in wireless synchronization designed for group or team settings, the validity of IMU-Tennis is consistent with, and in some cases exceeds, the fundamental measurement accuracy described in prior work on IMU-based assessment in wheelchair sport and mobility monitoring. At the same time, it should be emphasized that even though IMU platforms are generally grounded in the same sensing principles (i.e., the use of accelerometers and gyroscopes), they can differ markedly in several practical dimensions that include data acquisition and processing pipelines, calibration procedures, options for sensor placement, device cost, battery performance, and overall user experience. These practical considerations, together with evidence of measurement validity, should be weighed carefully when selecting an IMU solution for a particular research question or applied setting (4,27).

Nevertheless, future studies should collect the kinematics data from the real wheelchair tennis athletes in real situations, such as in training or competitive sessions. Moreover, additional IMU should be installed at the wrist of wheelchair users to analyze the movement of the upper limbs as well, and a wider variety of testing methods should be used for analyzing the physical fitness of wheelchair tennis (e.g., the test of the rotational speed and the degree of rotation).

CONCLUSIONS

The developed IMU-Tennis in this research study can be used to measure the traveling distance, velocity, and time of wheelchair users. The IMU-Tennis is made from the M5Stack Board that is equipped with the linear acceleration sensor and the angular velocity sensor. The IMU system collects and transmits the data via Bluetooth within 30 meters, with an operating frequency of 100 Hz. The system provides the output on the display monitor that the coach can use to track, store, and analyze the skill and fitness of the wheelchair tennis athletes.

According to the research data, the researchers found that the use of a developed IMU-Tennis to track a wheelchair tennis kinematics, in comparison to the use of a 2DMA, yields an acceptable level of percentage error with no significant difference in the measurement results and that there is a high level of correlation of the measurement results, whether it is distance, velocity, or time. These findings indicate that the developed IMU-Tennis used in this study shows high validity compared with 2DMA in setting situations.

AUTHOR CONTRIBUTIONS

Supachai Vorapojpisut: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration and Resources, Supervision.

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Light- and Moderate-Intensity Aerobic Exercise Do Not Significantly Alter Serum Tumor Necrosis Factor-Alpha in Diet-Induced Obese Wistar Rats: A Pilot Study

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ABSTRACT

Salikunna NA, Idris I, Cangara H, Badaruddin R, Rahmi MAB, Ar-Rahman SD, Sulistiana R, Syamsi N, Fitriani J. Chronic low-grade adipose tissue inflammation, marked by elevated tumor necrosis factor-alpha (TNF- α), links obesity to its downstream metabolic complications. Regular aerobic exercise is widely recommended to lower this inflammatory burden, but whether the intensity of exercise governs the magnitude of the response in an obese host remains incompletely defined, particularly in early-phase interventions. This pilot study compared the effect of light- and moderate-intensity treadmill exercise on serum TNF- α in diet-induced obese Wistar rats. Nine male Wistar rats (*Rattus norvegicus*), one month of age, were fed a high-calorie diet (CP551 plus 7 g·day⁻¹ milk powder) until a Rohrer Index ≥ 30 confirmed obesity, then allocated to 3 Groups (n = 3 each): the Sedentary Obese Control Group, the Light-Intensity Exercise Group (45% of VO₂max), and the Moderate-Intensity Exercise Group (60% of VO₂max). Exercise was performed on an animal treadmill for 6 weeks (5-min warm-up, 30-min core session, 5-min cool-down). Serum TNF- α was measured by ELISA at the end of the intervention. One-way ANOVA showed no significant difference in TNF- α among the 3 Groups (F = 1.037, P = 0.410), and the Tukey's *post hoc* Test found no significant pairwise differences. Mean TNF- α was numerically higher in both Exercise Groups (light: 26.75 $\pm$ 11.63; moderate: 21.03 $\pm$ 10.85) than in the Sedentary Obese Control Group (15.90 $\pm$ 1.61), although the wide variance and small sample preclude a firm conclusion. These preliminary findings do not demonstrate an anti-inflammatory effect of 6 weeks of light- or moderate-intensity exercise on TNF- α in obese rats and instead highlight the need for an adequately powered trial with a longer intervention period and multiple sampling points to characterize the time course of the response.

Key Words: Exercise Intensity, Obesity, TNF-alpha, Wistar Rat

INTRODUCTION

Obesity has become one of the defining public health challenges of the present century, with global estimates indicating that hundreds of millions of adults and children now live with excess adiposity (10,12). Beyond its cosmetic burden, obesity is a multifactorial disease shaped by genetic predisposition, gut microbial composition, and environmental drivers such as diet and physical inactivity (12,20,23), and it manifests across a spectrum of metabolic phenotypes and biomarker profiles (20). Even in children, genetic and syndromic forms of obesity illustrate how deeply weight regulation is embedded in central neuroendocrine pathways, although these monogenic causes account for only a minority of cases (9). Regardless of the etiology, the common downstream feature of excess adiposity is a state of chronic low-grade inflammation.

Enlarged, dysfunctional adipocytes recruit macrophages that polarize toward a pro-inflammatory phenotype and secrete excess free fatty acids, reactive oxygen species, and cytokines, chief among them tumor necrosis factor- α (TNF- α) (1). This cytokine is central to the paracrine loop between adipocytes and macrophages that sustains systemic inflammation and, over time, disrupts insulin signaling (1,10). Elevated TNF- α has also been implicated in sex-specific patterns of circulating monocyte activation in diet-induced obesity (3), and it may interact with adipose-resident immune and stromal cell populations relevant to emerging cell-based therapies for metabolic disease (2). Because obesity and its psychological correlates (such as depression) are each independently associated with reduced habitual physical activity, breaking this cycle through structured exercise is a recurring therapeutic target (22).

Rodent models of diet-induced obesity, particularly in Wistar rats, remain the most practical way to isolate the physiological effect of an exercise intervention from the many confounders present in free-living humans (24), and the Wistar strain in particular shows a pronounced and reproducible metabolic response to high-fat or high-calorie feeding compared with other outbred strains (18). Exercise is generally assumed to lower circulating TNF- α , and this has been demonstrated in some rodent and human studies of moderate-intensity training (13), and comparative work in obese mice has further suggested that the magnitude of the anti-inflammatory effect on adipose tissue TNF- α depends on exercise intensity, with higher-intensity protocols outperforming moderate-intensity continuous exercise (17). However, this dose-response relationship is not consistent across the literature. Several human trials have reported no change or even a transient increase in TNF- α shortly after an exercise bout, which is attributed to the acute phase of the cytokine response before its anti-inflammatory resolution takes hold (8,13). Hypoxic and altitude-based exercise paradigms illustrate a related principle, that the physiological stimulus accompanying an exercise protocol, not merely its duration, drives adipose tissue remodeling (7), while forced or unaccustomed exercise can itself act as a physiological stressor that transiently raises inflammatory markers rather than lowering

them (25). Therefore, a standardized, low-stress treadmill protocol is important for isolating the effect of intensity itself (16).

What remains poorly characterized is the comparative, early-phase effect of low-intensity versus moderate-intensity aerobic exercise on TNF- α specifically in a diet-induced obese rodent model, as opposed to comparisons restricted to moderate versus high or high-intensity interval protocols (17). Clarifying whether a light-intensity program confers a measurable anti-inflammatory benefit, or whether a minimum intensity threshold around 60% of VO₂max is required, has direct relevance for prescribing feasible exercise regimens to individuals with obesity who cannot immediately tolerate vigorous training. Hence, the purpose of this study was to compare the effect of 6 weeks of light-intensity (45% VO₂max) and moderate-intensity (60% VO₂max) treadmill exercise on serum TNF- α in diet-induced obese Wistar rats.

METHODS

Subjects

Nine male Wistar rats (*Rattus norvegicus*), one month of age and weighing 50–70 g, were obtained from PT. Gold Mice Farm and housed in the Physiology Laboratory, Faculty of Medicine, Tadulako University, under a natural circadian rhythm and an ambient temperature of 26–30°C. Following a 7-day acclimatization period, obesity was induced with a high-calorie diet (CP551 chow supplemented with 7 g·day⁻¹ full-cream milk powder) until each animal reached a Rohrer Index (RI) ≥ 30 , calculated as $RI = [\text{body weight (g)} / \text{naso-anal length (cm)}^3] \times 10^3$; an RI above 30 was taken to indicate obesity (14), consistent with high-calorie diet protocols used in other Wistar rat models of obesity from the same research group (14). This diet-induced approach mirrors polygenic, diet-based models of obesity that are generally regarded as more representative of the common human phenotype than monogenic or surgical models (24). Obesity was maintained for a further 6 weeks before the exercise intervention began. The animals were then allocated to 3 Groups of 3 rats each: (a) the Sedentary Obese Control Group; (b) the Light-Intensity Exercise Group; and (c) the Moderate-Intensity Exercise Group. All the procedures were approved by the Health Research Ethics Committee, Faculty of Medicine, Tadulako University (Ethical Clearance No. 1507/UN28.10/KL/2025).

Procedures

Exercise training was performed on a small-animal treadmill (SA101B, Jiangsu Cyons Biotechnology Co., Ltd.). Before the intervention, the rats underwent a 7-day treadmill adaptation period, during which maximal oxygen uptake (VO₂max) was estimated for each animal. The 6-week training session consisted of a 5-minute warm-up, a 30-minute core exercise bout, and a 5-minute cool-down. Individual exercise intensity was prescribed from the VO₂max index formula of Brooks and White (4), subsequently applied

by other investigators using the same treadmill paradigm (6): $\text{VO}_2\text{max index} = \text{treadmill speed (m} \cdot \text{min}^{-1}) \times \text{incline (\%)} \times 100 \times \text{body weight (kg)}$. The Light-Intensity Group trained at 45% of VO_2max and the Moderate-Intensity Group at 60% of VO_2max . This warm-up/core/cool-down structure and the range of relative intensities used are consistent with recently proposed low-stress treadmill protocols intended to elicit a genuine aerobic training adaptation without confounding the outcome with the physiological stress of a noxious stimulus (7). At the end of the 6-week intervention, blood was drawn and serum TNF- α concentration was measured using a commercial ELISA kit (catalog no. RK00029, ABclonal).

Statistical Analyses

The data were analyzed using IBM SPSS Statistics. The Shapiro-Wilk Test was used to assess the normality of TNF- α values within each Group. Because the assumption of normality was satisfied for all 3 Groups, a one-way analysis of variance (ANOVA) was used to compare mean serum TNF- α concentrations across the Sedentary Obese Control Group, the Light-Intensity Group, and the Moderate-Intensity Group, followed by Tukey's honestly significant difference (HSD) *post hoc* Test for pairwise comparisons. A significance level of $\alpha = 0.05$ was adopted throughout. Given the small group size ($n = 3$ per group), formal power calculations were not performed a priori. This study is presented as a pilot investigation that is intended to inform the sample size of a subsequent, adequately powered trial.

RESULTS

The Shapiro-Wilk Test on the research data showed that TNF- α levels were normally distributed in the Sedentary Obese Control Group ($P = 0.648$), the Light-Intensity Exercise Group ($P = 0.260$), and the Moderate-Intensity Exercise Group ($P = 0.095$), thus supporting the use of a parametric one-way ANOVA. Descriptive statistics for serum TNF- α by Group are presented in Table 1. Mean TNF- α was 15.90 ± 1.61 in the Sedentary Obese Control Group, 26.75 ± 11.63 in the Light-Intensity Exercise Group, and 21.03 ± 10.85 in the Moderate-Intensity Exercise Group, against an overall sample mean of 21.22 ± 9.27 ($N = 9$).

One-way ANOVA showed no statistically significant difference in serum TNF- α among the 3 Groups ($F^{2,6} = 1.037$, $P = 0.410$). Tukey's HSD *post hoc* comparisons likewise found no significant pairwise differences: (a) Sedentary Obese Control versus Light-Intensity Exercise (mean difference -10.85 , $P = 0.381$); (b) Sedentary Obese Control versus Moderate-Intensity Exercise (mean difference -5.13 , $P = 0.783$); and (c) Light-Intensity Exercise versus Moderate-Intensity Exercise (mean difference 5.72 , $P = 0.740$). Consistent with this, homogeneous subset analysis placed all 3 Groups within a single subset at $\alpha = 0.05$, indicating that the data did not support statistically distinguishable subgroups.

Numerically, both Exercise Groups showed higher, rather than lower, mean TNF- α than the Sedentary Obese Control Group, with the Light-Intensity Group showing the highest mean value and the widest variability of the 3 Groups. However, in view of the non-significant omnibus test, the very small sample size, and the wide confidence intervals evident in Table 1, this numerical pattern should be interpreted with caution and not as evidence of a pro-inflammatory effect of exercise.

Table 1. Descriptive Data of Serum TNF- α (pg·mL⁻¹) by Group.

Group	n	Mean $\pm$ SD	Minimum	Maximum	P*
Obese Sedentary Control	3	15.90 $\pm$ 1.61	14.49	17.65	Ref.
Light-Intensity Exercise	3	26.75 $\pm$ 11.63	13.44	34.98	0.381
Moderate-Intensity Exercise	3	21.03 $\pm$ 10.85	14.23	33.54	0.783
Total	9	21.22 $\pm$ 9.27	13.44	34.98	—

Values are mean $\pm$ SD. One-way ANOVA: $F_{2,6} = 1.037$, $P = 0.410$ (overall comparison across the 3 Groups). *P = Tukey's HSD *post hoc* P-value versus the Obese Sedentary Control Group (Ref.); no pairwise or overall comparison reached statistical significance ($P > 0.05$ throughout). Unit assumed as pg·mL⁻¹ per the manufacturer's ELISA kit reference range and should be confirmed against the original assay report.

DISCUSSION

TNF- α as a Marker of Obesity-Related Inflammation

TNF- α is one of the principal cytokines released by hypertrophied, macrophage-infiltrated adipose tissue in obesity, and it sits at the center of the paracrine signaling loop that couples adipocyte stress to systemic low-grade inflammation and, ultimately, to impaired insulin action (1,10). Because this inflammatory tone is thought to be reversible with weight loss and physical activity, TNF- α is frequently used as a sentinel outcome in exercise-intervention studies conducted in diet-induced obese rodents (13,17).

Exercise Intensity and TNF- α : Comparison with Prior Work

The statistical analysis indicates no significant decrease in TNF- α in either the Low-Intensity or Moderate-Intensity Groups. These results differ from several reports that indicated a decrease in this cytokine as a result of exercise. In a study of obese, intermittently fasted Wistar rats, 8 weeks of moderate-intensity exercise was associated with significantly lower TNF- α compared with the sedentary, high-fat-fed controls (13).

Similarly, in a comparative study of obese mice, moderate-intensity, high-intensity, and high-intensity-intermittent aerobic exercise all lowered adipose tissue TNF- α relative to the sedentary obese controls, although the higher-intensity protocols produced a significantly greater reduction than the moderate-intensity continuous exercise at both 4 and 8 weeks (17). Taken together with the present findings, this raises the possibility that 60% of VO₂max, the intensity used for the Moderate-Intensity Group here, sits below the threshold needed to elicit a measurable anti-inflammatory effect within a 6-week window, particularly in a rat model rather than the mouse models used in most of the intensity-comparison literature.

Evidence Supporting a Null or Paradoxical TNF- α Response to Exercise

Importantly, the assumption that exercise training uniformly lowers TNF- α is itself not well supported once the rodent literature is examined closely, and several primary studies report findings that run counter to this general hypothesis. In diet-induced obese Wistar rats, 8 weeks of high-intensity interval training failed to reduce visceral adipose tissue or to improve the broader inflammatory profile, including TNF- α , despite a measurable gain in maximal exercise capacity (5), which indicates that an exercise stimulus can be physiologically effective (improving fitness) without translating into a lower inflammatory tone. More directly, an early mechanistic study in Wistar rats found that 9 weeks of treadmill exercise training significantly increased, rather than decreased, TNF- α secretion from isolated adipocytes, together with reduced secretion of the soluble TNF receptor and greater expression of its membrane-bound form that is an adaptation the authors interpreted as evidence of enhanced, not diminished, autocrine TNF- α signaling within trained adipocytes (15). A comparable pattern was reported very recently in Wistar rats subjected to 8 weeks of endurance treadmill training: transmembrane TNF- α and IL-6 protein levels rose, rather than fell, in the lungs, liver, skeletal muscle, and heart, an increase that tracked tissue hypoxia markers and was interpreted as part of a systemic training adaptation rather than a pathological response (11). When considered together, these 3 studies indicate that the exercise-induced increase in TNF- α — rather than its suppression — has an independent basis in both the Wistar rat model and other rat models, thereby providing a physiological basis for the numerically higher TNF- α levels observed in the Light-Intensity Group and the Moderate-Intensity Group in the present study, beyond mere sampling variability, even though the comparisons in this study did not reach statistical significance.

Possible Explanations for the Absence of a Significant Effect

Our pilot study's methodological aspects make it plausible that there was a null or inverse effect on TNF- α , even though exercise actually has a genuine anti-inflammatory effect in this model. First, the sample size of 3 animals per Group is far below what is normally required to detect a moderate effect size with a cytokine assay of this variability, and the wide standard deviations in the exercise Groups (11.63 and 10.85, versus 1.61 in the

sedentary control) indicate that individual variation, rather than a true group difference, is likely to dominate the ANOVA result. Second, TNF- α and related cytokines can rise transiently in the acute phase after an exercise bout before an anti-inflammatory cascade, partly mediated by exercise-induced interleukin-6, brings levels back down (8); a single post-test sample at the end of the intervention cannot distinguish an acute peri-exercise elevation from the animal's true resting, chronically adapted state. Some human studies have similarly reported no significant change, or even a numerical increase in TNF- α after a period of low-to-moderate intensity walking or treadmill exercise (13), which underscores that a decline in TNF- α with exercise is not a universal finding. Third, unaccustomed treadmill exercise, even when protocolized to minimize noxious stimuli, can itself act as a physiological and psychological stressor in rodents, and forced exercise paradigms have been shown to raise corticosterone and downstream inflammatory markers rather than lower them (25); the Light-Intensity Group's relatively higher TNF- α in the present study may partly reflect this competing stress response outweighing any anti-inflammatory training adaptation over only 6 weeks.

Strengths and Limitations

This study used a well-characterized diet-induced obesity model with an objectively defined obesity threshold (Rohrer Index ≥ 30) and a treadmill protocol with individualized VO_2max -referenced intensity prescription, which are features that improve on obesity models relying only on visual assessment or fixed workloads. The principal limitation is the small number of animals per group ($n = 3$) that severely limits statistical power and precludes any claim of equivalence between exercise and no exercise, which is consistent with the wide confidence intervals in Table 1. The single end-point blood draw, the absence of an intermediate sampling point, and the lack of a matched non-obese comparison group further limit interpretation. Future work with a larger sample, repeated sampling across the intervention, and a wider range of exercise intensities, including a higher-intensity arm consistent with prior mouse data, would help clarify whether a genuine dose-response relationship between exercise intensity and TNF- α exists in this model.

CONCLUSIONS

In this pilot study of diet-induced obese Wistar rats, 6 weeks of light-intensity (45% VO_2max) or moderate-intensity (60% VO_2max) treadmill exercise did not produce a statistically significant change in serum TNF- α compared when compared to the sedentary obese controls. Also, the numerical direction of change was, if anything, opposite to the anti-inflammatory effect generally hypothesized. These findings should be regarded as hypothesis-generating rather than conclusive, given the very small sample size. Also, the findings support the design of a larger, adequately powered study with

repeated sampling to characterize the time course of the TNF- α response to exercise intensity in this model.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

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Effects of Social Dance and Yoga Combined with Social Dance on Physical and Mental Health in Undergraduate Students

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ABSTRACT

Sungtes S, Peepathum P, Vongchaisub TS. Effects of Social Dance and Yoga Combined with Social Dance on Physical and Mental Health in Undergraduate Students. University students frequently face physical and mental health challenges, necessitating effective multi-dimensional interventions. This study examined and compared the effects of social dance alone and in combination with yoga on undergraduate students' physical and mental health. Fifty-five first-year students (19 to 22 years of age) were assigned to 3 groups: (a) Control Group (n = 19); (b) Social Dance Group (n = 18); and (c) Combined Yoga and Social Dance Group (n = 18). The 8-week intervention consisted of 60-minute sessions conducted 3 days per week. Assessments of physical and mental health parameters occurred at baseline, week 4, and week 8. The data were analyzed using One-way ANOVA and One-way Repeated Measures ANOVA ($P < 0.05$). The results indicated that after 8 weeks, both the Social Dance Group and the Combined Yoga and Social Dance Group exhibited significant within-group improvements in overall physical fitness and mental health compared to baseline ($P < 0.05$), notably decreasing stress levels while improving cardiorespiratory endurance, muscular strength, and body composition; whereas, the Control Group showed no significant changes. Furthermore, at week 8, the Combined Yoga and Social Dance Group demonstrated significantly superior outcomes in stress reduction, flexibility, core endurance, and body composition compared to both the Social Dance Group and the Control Group ($P < 0.05$). However, cardiorespiratory endurance, leg strength, and balance did not differ significantly between the 2 active interventions ($P > 0.05$). In conclusion, integrating yoga with social dance provides a highly effective holistic intervention for comprehensively enhancing well-being. These findings demonstrate that a multi-modality exercise regimen yields superior health benefits in university students compared to a single-modality program.

Key Words: Mental Health, Physical Health, Social Dance, Undergraduate Students, Yoga

INTRODUCTION

Currently, people of all ages value physical exercise, recognizing its profound physical and mental benefits. Regular physical activity helps to slow physiological decline, enhances cardiovascular fitness, muscular strength, and flexibility, and improves mobility and balance (4,18). Additionally, it promotes mental health, reduces stress, and increases self-esteem (1,17). In Thailand, undergraduate students often experience a marked decline in physical activity due to academic demands and lifestyle changes that lead to rapid weight gain and an increase in percentage of body fat (PBF) beyond healthy thresholds. Consequently, they face an increased risk of non-communicable diseases (NCDs), such as diabetes and hypertension (11). For first-year undergraduate students, the transition to university life often involves high levels of stress and a significant need for adaptation. Regular physical activity plays a crucial role in helping students balance their emotions and build broader social relationships and mitigate severe academic stress (8,14,20,25).

Social dance involves rhythmic bodily movements to music. It is an activity that develops leg strength, cardiovascular endurance, and balance, while simultaneously inducing relaxation and promoting overall mental health (6). Several studies indicate that dance interventions, such as an 8-week social dance program, not only improve physical fitness more effectively than some other physical activities but also significantly reduce stress and elevate emotional well-being in students (7,10,15). Moreover, recent evidence within the exercise physiology literature highlights that structured dance and aerobic protocols effectively enhance cardiopulmonary function and body composition in young adult populations (21).

Yoga, a mind-body practice that incorporates various postures integrated with breathing exercises can be performed either dynamically or statically (23). It effectively increases flexibility, cultivates mindfulness, and significantly alleviates both anxiety and stress (12,13). Previous studies have shown that an 8-week yoga intervention for first-year students, alongside other mind-body practices, helps manage academic-related stress and restores physiological balance (3,24). However, social dance training alone often causes muscle tension and fatigue, particularly in the legs, due to continuous standing and stepping in various directions. In contrast, yoga encompasses standing, seated, prone, supine, and side-lying postures that emphasize muscle stretching combined with deep breathing to induce comprehensive physical and mental relaxation. Hence, integrating these 2 activities could yield complementary benefits. Since no previous studies have investigated a combined social dance and yoga program among undergraduate students, this study compared the effects of combined yoga and social dance training versus social dance training alone. It is hypothesized that the combined training program will be more effective in improving both physical and mental health outcomes.

METHODS

Subjects

A total of 60 first-year undergraduate students from Rajamangala University of Technology Rattanakosin, Salaya Campus, Nakhon Pathom Province were initially recruited for this study. In accordance with the CONSORT guidelines (Figure 1), 3 volunteers were excluded during the initial screening (two did not meet the inclusion criteria, and one declined to participate). The remaining 57 participants were randomly assigned to one of three groups: a Control Group ($n = 19$), a Combined Yoga and Social Dance Group ($n = 19$), and a Social Dance Group ($n = 19$). During the 8-week intervention, one participant from each experimental group withdrew

from the study. Consequently, a total of 55 participants successfully completed the study (Control Group, $n = 19$; Combined Group, $n = 18$; Social Dance Group, $n = 18$). The Inclusion Criteria were as follows: (a) aged 19–22 years; (b) no participation in yoga or social dance within the past 6 months; (c) a sedentary lifestyle (non-athletes); (d) no medical contraindications to exercise; (e) a normal body mass index (BMI 18.5–22.9 kg/m²); and (f) low-to-normal stress levels (total score ≤ 41). Participants were excluded if they developed health issues during the intervention, attended fewer than 70% of the training sessions, or voluntarily withdrew from the study. All the participants were informed of the purpose, the procedures, and the potential risks prior to the study. The research procedures were approved by the Human Research Ethics Committee, Srinakharinwirot University.

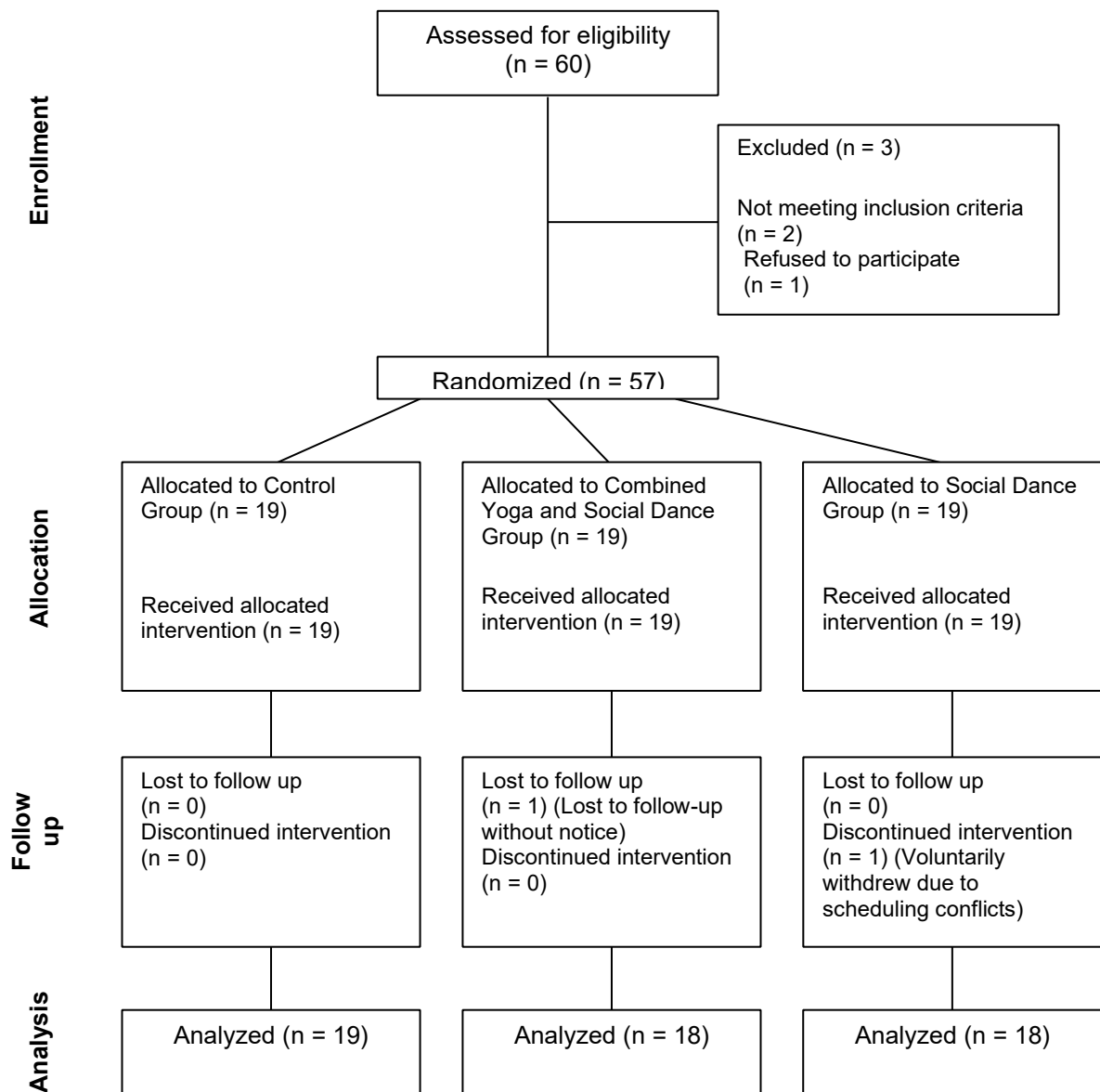


Figure 1. CONSORT Flow Diagram of the Participant Allocation and Analysis Procedures.

This study was designed as a randomized controlled trial (RCT). To ensure baseline equivalence among the groups, the participants were initially ranked based on their pre-training leg strength scores, systematically distributed, and randomly assigned to one of the three groups by drawing lots. The data were collected at 3 time points: baseline, week 4, and week 8 of the intervention. The physical health assessment included 8 variables: (a) leg strength, (b) cardiovascular endurance, (c) flexibility, (d) core muscle endurance, (e) balance, (f) PBF, (g) BMI, and (h) resting heart rate (RHR). Additionally, mental health evaluations included the measurement of general mental health and stress levels.

The intervention program spanned 8 weeks, with training sessions conducted 3 days per week, as presented in Table 1. Each session lasted 60 minutes and was consistently scheduled between 5:00 and 6:00 pm. The Combined Yoga and Social Dance Group trained on Mondays, Wednesdays, and Fridays. Their sessions consisted of a 10-minute warm-up, 20 minutes of yoga (17 predefined asanas concluding with deep breathing in Savasana), 20 minutes of social dance, and a 10-minute cool-down. The Social Dance Group trained on Tuesdays, Thursdays, and Saturdays. Their sessions consisted of a 10-minute warm-up, 40 minutes of social dance, and a 10-minute cool-down. The dance curriculum involved the Rumba rhythm for weeks 1–4 and the Cha-Cha-Cha rhythm for weeks 5–8. The Control Group was instructed to maintain their regular daily routines without participating in structured exercise.

Table 1. Intervention Protocols and Training Characteristics Across Study Groups.

Training Component	Combined Yoga and Social Dance Group	Social Dance Group
Frequency	3 days/week (Monday, Wednesday, Friday)	3 days/week (Tuesday, Thursday, Saturday)
Warm-Up	10 minutes	10 minutes
Main Exercise (Weeks 1-4)	40 minutes total • 20 min yoga (17 Asanas including Savasana) • 20 min Social Dance (Rumba, 25-27 bars/min)	40 minutes total • 40 min Social Dance (Rumba, 25-27 bars/min)
(Weeks 5-8)	40 minutes total • 20 min yoga (17 Asanas including Savasana) • 20 min Social Dance (Cha-Cha-Cha, 30-32 bars/min)	40 minutes total • 40 min Social Dance (Cha-Cha-Cha, 30-32 bars/min)
Cool-Down	10 minutes	10 minutes
Total Duration	60 minutes/session	60 minutes/session

Measurements

Various standardized instruments and testing protocols were employed to assess the participants' physical and mental health parameters. Physiological baselines, including blood pressure and RMR, were measured using an automatic arm-in blood pressure monitor (OMRON model HEM-1000, China), while body composition was analyzed using a digital body composition monitor (OMRON model HBF-375, South Korea). To evaluate physical fitness components, cardiovascular endurance was assessed via the Queen's College Step Test (1), and leg strength was measured using a Leg Strength Dynamometer (1).

Flexibility was evaluated using a standard sit-and-reach box (1), balance was determined through the Y-Balance Test (19), and core muscle endurance was tested using the Plank Test (2). Furthermore, the subjects' psychological variables were assessed using 2 standardized questionnaires: (a) general mental health was evaluated with the 55-item Thai Mental Health Indicator (TMHI-55) (17); and (b) stress levels were measured using the Suanprung Stress Test-20 (SPST-20) (16).

Statistical Analyses

The data were analyzed using IBM SPSS Statistics (version 31.0). The Shapiro-Wilk Test was used to verify the normality of the data distribution. Descriptive statistics (mean $\pm$ SD) were calculated for demographic variables. Between-group differences among the 3 Groups at baseline, week 4, and week 8 were analyzed using a one-way analysis of variance (ANOVA). Within-group differences across the 3 time points were evaluated using a one-way repeated measures ANOVA. Significant main effects were further analyzed using Bonferroni *post hoc* tests. Statistical significance was set at $P < 0.05$.

RESULTS

Table 2 presents the baseline descriptive characteristics of the participants, divided into 3 distinct groups: (a) the Control Group ($n = 19$); (b) the Combined Yoga and Social Dance Group ($n = 18$); and (c) the Social Dance Group ($n = 18$). The sex distribution reveals that the Control Group consisted of 15 males and 4 females. The Combined and Social Dance Group and the Social Dance Group consisted of 13 males and 5 females in each Group.

The mean age of the participants was relatively similar across the 3 Groups: (a) the Control Group recorded at 19.63 ± 0.68 years; (b) the Combined Yoga and Social Dance Group recorded at 19.22 ± 0.43 years; and (c) the Social Dance Group recorded at 19.39 ± 0.85 years. for the social dance group. In terms of physical characteristics, the average heights were 169.00 ± 6.22 cm, 168.94 ± 5.68 cm, and 167.72 ± 9.44 cm for the Control, the Combined Yoga and Social Dance Group, and the Social Dance Group, respectively. Additionally, the mean body weights were observed at 61.15 ± 5.78 kg for the Control Group, 57.47 ± 6.36 kg for the Combined Yoga and Social Dance Group, and 62.00 ± 8.41 kg for the Social Dance Group.

Table 2. Descriptive Characteristics of the Participants (Mean $\pm$ SD).

Variable	Control Group (n = 19)	Combined Yoga and Social Dance Group (n = 18)	Social Dance Group (n = 18)
Sex (number)			
Male	15	13	13
Female	4	5	5
Age (yr)	19.63 $\pm$ 0.68	19.22 $\pm$ 0.43	19.39 $\pm$ 0.85
Height (cm)	169.00 $\pm$ 6.22	168.94 $\pm$ 5.68	167.72 $\pm$ 9.44
Weight (kg)	61.15 $\pm$ 5.78	57.47 $\pm$ 6.36	62.00 $\pm$ 8.41

Table 3 presents a comprehensive comparison of the mental and physical health outcomes among the 3 Groups across the 8-week intervention.

Baseline and Week 4 Between-Group Comparisons

At baseline, there were no significant differences among the 3 Groups across most mental and physical health variables ($P > 0.05$) that indicated Group equivalency prior to the intervention. The only exception was TMHI, where the Combined Group exhibited a significantly lower score compared to the Control Group ($P = 0.037$). Following 4 weeks of the intervention, between-group comparisons revealed no significant differences across any of the measured mental or physical health parameters ($P > 0.05$).

Within-Group Comparisons Across the 8-Week Intervention

Within-group analyses indicated that the Control Group maintained stable outcomes, showing no significant changes in any mental or physical health parameters from baseline to week 8. Conversely, both the Combined Yoga and Social Dance Group and the Social Dance Group alone demonstrated progressive, significant improvements. By week 4, both the Combined Yoga and Social Dance Group and the Social Dance Group exhibited significant enhancements compared to their baseline values ($P < 0.05$) across all mental and physical variables. These positive adaptations were further sustained and significantly augmented by week 8, with both Groups showing significant improvements compared to their week 4 outcomes ($P < 0.05$).

Week 8 Between-Group Comparisons

Distinct between-group differences emerged at the end of the 8-week intervention. The Combined Yoga and Social Dance Group demonstrated significantly superior outcomes compared to the Control Group in stress reduction ($P < 0.001$), flexibility ($P < 0.001$), core endurance ($P = 0.001$), PBF ($P = 0.006$), and BMI ($P < 0.001$). The Social Dance Group also showed significant improvements over the Control Group in stress levels, cardiovascular endurance, and BMI ($P < 0.05$). Notably, when comparing the 2 active interventions at week 8, the combined training program was significantly more effective than social dance alone in

reducing stress levels, as well as enhancing flexibility and core muscle endurance ($P < 0.05$). However, no significant between-group differences were observed at week 8 concerning TMHI, leg strength, balance (left and right), and RHR ($P > 0.05$).

Table 3. Comparison of Mental and Physical Health Outcomes Among the Groups Across the 8-Week Intervention.

Variable	Control Group	Combined Yoga and Social Dance Group	Social Dance Group	F	P-value
MENTAL HEALTH					
(TMHI)					
baseline	172.79 ± 17.60	163.33 ± 3.34*	165.94 ± 6.82	3.52	0.037
week 4	172.68 ± 15.28	169.94 ± 4.11 [^]	169.11 ± 6.33 [^]	0.65	0.524
week 8	169.32 ± 8.28	174.11 ± 5.68 ^{^\$}	173.44 ± 7.63 ^{^\$}	2.36	0.104
Stress Level (SPST)					
baseline	35.16 ± 4.96	34.44 ± 4.84	35.11 ± 4.81	0.12	0.885
week 4	35.47 ± 4.01	32.39 ± 4.75	34.72 ± 4.79	2.32	0.109
week 8	37.53 ± 5.54	28.06 ± 4.33* ^{^\$}	32.28 ± 4.68* ^{^\$}	17.44	<0.001
PHYSICAL HEALTH					
Leg Strength (kg/kg BW)					
baseline	1.76 ± 0.53	1.90 ± 0.68	1.72 ± 0.52	0.44	0.649
week 4	1.78 ± 0.52	2.02 ± 0.68 [^]	1.81 ± 0.53 [^]	0.93	0.401
week 8	1.80 ± 0.49	2.23 ± 0.64 ^{^\$}	1.95 ± 0.56 ^{^\$}	2.66	0.080
Cardiovascular (ml/kg/min)					
baseline	45.47 ± 8.33	43.79 ± 5.27	45.56 ± 9.09	0.30	0.744
week 4	44.60 ± 8.28	46.28 ± 5.59 [^]	47.36 ± 9.53 [^]	0.56	0.573
week 8	44.97 ± 8.09	50.32 ± 6.36 ^{^\$}	51.55 ± 9.37* ^{^\$}	3.53	0.037
Flexibility (cm)					
baseline	5.68 ± 12.03	7.72 ± 7.25	7.33 ± 8.25	0.24	0.785
week 4	5.84 ± 11.56	11.39 ± 6.76 [^]	8.61 ± 7.98 [^]	1.74	0.186
week 8	4.89 ± 11.31	17.44 ± 5.32* ^{^\$}	10.39 ± 7.31 ^{^\$}	10.29	<0.001
Core Endurance (min)					
baseline	1.52 ± 0.80	1.49 ± 0.79	1.21 ± 0.84	0.80	0.457
week 4	1.44 ± 0.72	1.85 ± 0.78 [^]	1.43 ± 0.71 [^]	1.92	0.156
week 8	1.56 ± 0.79	2.40 ± 0.74* ^{^\$}	1.63 ± 0.66 ^{^\$}	7.43	0.001
Balance					
- Left Leg (%)					
baseline	48.47 ± 9.54	46.06 ± 6.77	52.33 ± 7.61	2.76	0.072
week 4	48.05 ± 9.13	48.67 ± 6.67 [^]	53.06 ± 7.89	2.13	0.129
week 8	48.26 ± 8.62	50.44 ± 5.93 ^{^\$}	54.39 ± 8.05 ^{^\$}	3.03	0.057
- Right Leg (%)					
baseline	48.58 ± 9.68	45.89 ± 5.79	51.28 ± 8.99	1.87	0.164
week 4	48.63 ± 8.60	48.00 ± 6.26 [^]	52.33 ± 9.78	1.42	0.250
week 8	48.21 ± 7.99	49.83 ± 5.91 ^{^\$}	53.22 ± 9.69 ^{^\$}	1.87	0.164
PBF (%)					
baseline	22.06 ± 1.97	19.91 ± 6.75	22.97 ± 4.32	2.00	0.146
week 4	22.40 ± 1.95	19.08 ± 6.68 [^]	22.29 ± 4.58	2.84	0.067
week 8	22.52 ± 1.78	17.69 ± 6.30* ^{^\$}	21.03 ± 4.13 ^{^\$}	5.71	0.006
BMI (kg/m²)					

Variable	Control Group	Combined Yoga and Social Dance Group	Social Dance Group	F	P-value
baseline	21.63 ± 0.55	20.67 ± 2.10	21.08 ± 1.31	2.07	0.137
week 4	21.09 ± 0.82	20.16 ± 1.99 [^]	20.89 ± 0.97	2.39	0.102
week 8	21.44 ± 1.12	19.49 ± 1.87 ^{*^\$}	20.06 ± 0.96 ^{*^\$}	9.92	<0.001
RHR (bpm)					
baseline	80.95 ± 12.27	84.28 ± 10.40	84.39 ± 7.15	0.69	0.509
week 4	84.32 ± 13.02	81.89 ± 9.65 [^]	81.83 ± 6.42 [^]	0.37	0.696
week 8	83.11 ± 12.62	79.56 ± 9.07 ^{^\$}	79.83 ± 6.03 ^{^\$}	0.77	0.466

*Significantly different from the Control Group (P < 0.05).

#Significantly different from the Combined Yoga and Social Dance Group (P < 0.05).

[^]Significantly different from the baseline (P < 0.05).

^{\$}Significantly different from the week 4 (P < 0.05).

DISCUSSION

The primary objective of this study was to evaluate and compare the effects of a combined yoga and social dance program versus social dance alone on the physical and mental health of undergraduate students. We hypothesized that the combined training program would be more effective in comprehensively improving both physical and mental health outcomes compared to a single-modality exercise program. The findings of the present study largely support this hypothesis, demonstrating that integrating yoga with social dance yields superior holistic health benefits.

A pivotal finding of this study is that the Combined Yoga and Social Dance Group exhibited a statistically significant reduction in stress levels (SPST) compared to both the Social Dance only Group and the Control Group. Although dance is an activity that develops physical strength while promoting good mental health through musical rhythm and social interaction (6), and has been shown to elevate students' emotional well-being (15), the integration of yoga profoundly enhanced overall relaxation efficacy. Because yoga is a mind-body practice that integrates physical postures with breath control (23), it directly contributes to cultivating mindfulness, as well as reducing both anxiety and stress (12,26). These results align with the research of Tripathi et al. (24), which reported that an 8-week yoga program played a crucial role in helping first-year students manage academic pressure and restored autonomic balance during a highly demanding period of adaptation.

Regarding physical health, the Combined Yoga and Social Dance Group demonstrated significantly superior improvements in flexibility and core muscle endurance compared to the other 2 Groups. This outcome can be explained by the distinct physiological characteristics of the 2 activities. Social dance training alone frequently leads to muscle tension and fatigue, particularly in the lower extremities due to continuous standing and stepping. Conversely, yoga encompasses standing, sitting, prone, and supine postures that emphasize systematic muscle stretching paired with deep breathing. Thus, integrating yoga into the training program functions as a restorative mechanism that effectively alleviates dance-induced muscle tension, it supports physical recovery (9,22). This synergistic approach is consistent with Chainok et al. (5) who emphasized the critical role of combining aerobic elements with flexibility and core-stabilizing interventions to maximize functional capacity in collegiate populations.

Furthermore, the results indicate that both the Combined Yoga and Social Dance Group and the Social Dance Group itself without the Yoga achieved significantly better improvements in cardiovascular endurance, PBF, and BMI than the Control Group. This is consistent with the previous studies that regular exercise enhances cardiovascular fitness and metabolic health (4,18). The findings indicate that the Rumba and Cha-Cha-Cha social dance routines provide sufficient aerobic intensity to stimulate energy expenditure and cardiovascular function. Allocating 20 minutes for yoga within the combined session did not diminish the aerobic benefits of the dance. In fact, it acted as a complementary component that generated significant synergistic effects.

Limitations in this Study

Several limitations should be considered when interpreting these findings. First, the small, predominantly male sample of first-year students from a single university restricts the generalizability of the results to broader demographics. Second, the 8-week intervention precludes assessing long-term exercise adherence or the sustainability of the health benefits. Third, the reliance on self-reported questionnaires for psychological outcomes introduces potential response bias. Finally, extraneous lifestyle variables such as diet, sleep, and unmonitored physical activity outside of the structured sessions were not strictly controlled and could have influenced the overall outcomes.

CONCLUSIONS

The findings of this study demonstrate that an 8-week intervention of either social dance alone or a combination of yoga and social dance effectively improved the physical and mental health of undergraduate students. However, the combined yoga and social dance program resulted in superior holistic benefits. Specifically, integrating yoga into social dance training is significantly more effective than social dance alone in reducing psychological stress, as well as enhancing flexibility and core muscle endurance. Therefore, a multi-modality approach that combines mind-body practices like yoga with aerobic activities, such as social dance is highly recommended as a comprehensive and optimal exercise regimen to maximize both physical fitness and mental well-being in university populations.

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Acute Physiological and Locomotor Responses to Fixed-Area Transition Small-Sided Games of Different Pitch Sizes and Work-to-Rest Ratios in Soccer Players

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ABSTRACT

Chootsungnoen P, Sonchan W, Chainok P. Acute Physiological and Locomotor Responses to Fixed-Area Transition Small-Sided Games of Different Pitch Sizes and Work-to-Rest Ratios in Soccer Players. The purpose of this study was to describe the internal- and external-load responses of a fixed-area (no pitch-area change) transition small-sided game (SSG) format in which the players transitioned from defense to attack without altering the playing area across 3 pitch sizes (small, 75 m²·player⁻¹; medium, 100 m²·player⁻¹; large, 150 m²·player⁻¹) and 2 work-to-rest ratios (1:1, 4 min:4 min; 1:0.5, 4 min:2 min). Twenty-two male soccer players (N = 22) volunteered, forming 6 fixed 3-a-side teams that completed all 6 pitch-size × ratio conditions of the fixed-area format, supported in every trial by 4 floating attacking-support players who preserved the defense-to-attack transition structure. Heart rate (HR), rating of perceived exertion (RPE, Borg CR-10), and 10-Hz GPS-derived locomotor variables were recorded during each bout and analyzed with Jamovi. Across the 6 conditions, mean HR ranged from 151.0 ± 7.7 to 164.3 ± 9.6 beats·min⁻¹ (75.2 – 82.3% of HR_{max}), RPE ranged from 5.7 ± 0.9 to 7.8 ± 0.9, and total distance covered ranged from 1508.6 ± 212.6 to 2185.0 ± 265.2 m. The medium pitch produced the highest relative cardiovascular strain (%HR_{mean}, RPE) at both ratios; whereas, the total distance, high-speed running, and the number of accelerations /decelerations increased with pitch size and were consistently lowest on the small pitch. Shortening the recovery interval (1:0.5) increased RPE on the medium and large pitches but not on the small pitch. These findings indicate that, within a fixed-area transition SSG format, pitch size and work-to-rest ratio act on internal- and external-load markers in a non-uniform, partially dissociated manner, giving coaches 2 independent levers for prescribing the aerobic-technical training stimulus.

Key Words: Pitch Size, Small-Sided Games, Transition Play, Work-to-Rest Ratio

INTRODUCTION

Soccer match play imposes intermittent, high physiological demands on players, who cover 10 to 13 km per 90-min match while repeatedly performing high-intensity actions superimposed on low-to-moderate intensity activity (2,21). Small-sided games (SSGs) have become a cornerstone conditioning tool because they simultaneously train the aerobic and anaerobic energy systems while rehearsing technical and tactical skills in a match-representative context (1,14).

A key strength of SSGs is that their physiological and locomotor demands can be manipulated through simple task constraints. Pitch size, expressed as relative playing area per player, is one of the most studied constraints: larger pitches generally increase total distance, high-speed running, and sprint distance; whereas, smaller pitches tend to elevate relative heart-rate (HR) responses because of more frequent ball contacts and less space to recover between efforts (4,24). The work-to-rest ratio applied between bouts is a second, largely independent constraint: shortening the recovery interval relative to the work interval raises cardiovascular and perceptual strain within a training session, in a manner comparable to interval-training prescription (9,20).

Most of the pitch-size and work-to-rest literature has examined possession-based or unconstrained SSG formats. Comparatively less attention has been paid to transition-structured SSGs, in which players must switch rapidly between defending and attacking arguably one of the most decisive phases of match play and a format increasingly used to train the perceptual and physical demands of counter-attacking and counter-pressing play (6,12,13). Within transition SSGs, the playing area can either change size as the team in possession advances (variable-area format) or remain constant throughout the bout (fixed-area format). Because the 2 formats plausibly place different demands on players, the acute internal-load and external-load responses of the fixed-area transition format specifically across a systematic combination of pitch sizes and work-to-rest ratios have not, to the authors' knowledge, been reported in isolation.

Therefore, the purpose of this study was to describe the acute internal load (HR, RPE) and external load (GPS-derived locomotor) responses of a fixed-area transition small-sided game format across 3 pitch sizes (small, medium, and large) and two work-to-rest ratios (1:1 and 1:0.5) in male soccer players.

METHODS

Subjects

Twenty-two male soccer players (N = 22) from a competitive university squad volunteered for this study. All 22 players took part in the fixed-area transition SSG protocol: eighteen players were organized into 6 fixed 3-player teams and completed all 6 pitch-size × work-to-rest ratio conditions of the fixed-area format, while the remaining 4 players rotated across trials in a floating attacking-support role, joining whichever team held possession to preserve the defense-to-attack transition structure in every condition. Descriptive characteristics of the players comprising the 6 fixed 3-a-side teams are presented in Table 1. All players were free of musculoskeletal injury and had trained continuously for at least 6 months prior to testing. The participants (or their legal guardians, where applicable) provided written informed consent, and the study was approved by the affiliated university's research ethics committee prior to data collection. The study was approved by the Institutional Review Board of Burapha University (approval no. IRB3-023/2569; research project code G-HS105/2568) and was

conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants.

Procedures

The fixed-area transition SSG involved 3 three-player teams (distinguished by bib color) that occupied a single, unchanging playing area throughout the bout, supported by floating attacking players who joined whichever two teams held possession. At any time, 2 of the 3 teams combined in attacking possession against the third, defending team; loss of the ball by either attacking team, or a defined sequence of completed passes won by the defending team, triggered an immediate role switch, in which the team that lost possession became the new defending team while the team that won the ball joined the remaining team in attacking possession. Each bout was performed on 1 of 3 rectangular pitch sizes: (a) small (46×18 m; $75 \text{ m}^2 \cdot \text{player}^{-1}$); (b) medium (55×20 m; $100 \text{ m}^2 \cdot \text{player}^{-1}$); and (c) large (66×25 m; $150 \text{ m}^2 \cdot \text{player}^{-1}$). At each pitch size, the players completed bouts under 2 work-to-rest ratios: 1:1 (4 min of play followed by 4 min of recovery) and 1:0.5 (4 min of play followed by 2 min of recovery), yielding 6 pitch-size $\times$ ratio conditions in total. Conditions were performed on separate testing days in a randomized order. The spatial arrangement of players during a bout, including the floating attacking-support players, is illustrated in Figure 1.



Figure 1. Schematic Representation of Player Positioning during the Fixed-Area Transition Small-Sided Game within the Unchanging Playing Area, showing 3 Team Groupings (distinguished by playing bib color) and the 2 Floating Attacking-Support Players ("Free"), who Joined Whichever Team Held Possession.

Internal load was quantified continuously during every bout using a chest-worn heart rate monitor (Polar H10, Polar Electro, Kempele, Finland; reliability = 0.93) (27), from which HRmax, HRmean, the percentage of individual maximal HR (%HRmax, %HRmean), and the time spent within three HR zones (70–79%, 80–89%, and 90–100% of HRmax) were derived. Immediately after each bout, players rated their perceived exertion using Borg's CR-10 scale (3,17). External load was quantified using a 10-Hz global positioning system unit integrated with a tri-axial accelerometer (Catapult Vector S7, Catapult Sports, Melbourne, Australia) (22), worn between the scapulae, from which total distance covered, high-speed running distance, sprint distance, peak running speed, and the number of accelerations and decelerations were extracted.

Statistical Analyses

All internal and external load variables are presented as mean $\pm$ SD for each of the six pitch-size $\times$ work-to-rest ratio conditions of the fixed-area format. Data were analyzed with Jamovi (The Jamovi project, Sydney, Australia). Normality of the distributions was assessed with the Shapiro-Wilk Test. Because pitch size, transition-format (fixed- vs. variable-area), and work-to-rest ratio were manipulated jointly within the parent project, the full inferential model was a three-way repeated-measures ANOVA (Pitch Size $\times$ Format $\times$ Ratio) computed on the complete 18-player dataset (Table 4). This model, rather than a model restricted to the fixed-area format alone, is the source of the inferential statistics reported here; the rationale for reporting the fixed-area condition separately, and the corresponding limitation, are addressed in the Discussion. Statistical significance was accepted at $\alpha = .05$, and partial eta-squared (η^2p) was used to express effect size (7,15).

RESULTS

Descriptive characteristics of the 18 players comprising the six fixed 3-a-side teams are presented in Table 1.

Table 1. Descriptive Data of the Subjects.

Variable	Mean $\pm$ SD
Age (yrs)	21.5 $\pm$ 1.85
Height (cm)	177.61 $\pm$ 6.09
Weight (kg)	68.44 $\pm$ 7.61
BMI (kg·m ⁻²)	21.0 $\pm$ 1.79
Body Fat (%)	15.07 $\pm$ 3.41
VO ₂ max (mL·kg ⁻¹ ·min ⁻¹)	52.42 $\pm$ 1.48

BMI; Body Mass Index, **VO₂max**; Maximal Oxygen Uptake. Values are Mean $\pm$ SD.

Descriptive internal load and RPE responses of the fixed-area transition SSG format across the three pitch sizes and two work-to-rest ratios are presented in Table 2. Mean HR ranged from 151.0 $\pm$ 7.7 beats·min⁻¹ (large pitch, ratio 1:1) to 164.3 $\pm$ 9.6 beats·min⁻¹ (medium pitch, ratio 1:0.5), corresponding to 75.2–82.3% of HRmax. The medium pitch produced the highest %HRmean at both work-to-rest ratios (81.3 $\pm$ 5.4% at 1:1; 82.3 $\pm$ 4.7% at 1:0.5), whereas the large and small pitches produced comparable, lower values (75.2–77.8%). RPE increased from ratio 1:1 to 1:0.5 on the large pitch (7.1 $\pm$ 0.8 to 7.8 $\pm$ 0.9) and the medium pitch (5.9 $\pm$ 0.7 to 7.1 $\pm$ 1.1), but the small pitch showed the opposite trend, with RPE numerically lower at the shorter recovery ratio (6.1 $\pm$ 1.0 at 1:1 vs. 5.7 $\pm$ 0.9 at 1:0.5). Time spent above 90% HRmax was brief across all six conditions (2.4–20.0 s per bout on average).

Table 2. Internal-Load and RPE Responses of the Fixed-Area Transition SSG.

Variable	Large 1:1	Medium 1:1	Small 1:1	Large 1:0.5	Medium 1:0.5	Small 1:0.5
HRmax (bpm)	181.2 $\pm$ 4.7	176.9 $\pm$ 10.0	177.5 $\pm$ 6.4	183.4 $\pm$ 7.7	184.2 $\pm$ 6.7	173.7 $\pm$ 7.2
%HRmax	90.6 $\pm$ 2.4	88.7 $\pm$ 5.1	88.9 $\pm$ 3.2	91.8 $\pm$ 4.0	92.4 $\pm$ 3.3	87.2 $\pm$ 3.6
HRmean (bpm)	151.0 $\pm$ 7.7	162.1 $\pm$ 10.9	152.4 $\pm$ 6.4	160.7 $\pm$ 10.3	164.3 $\pm$ 9.6	155.0 $\pm$ 8.4
%HRmean	75.2 $\pm$ 3.8	81.3 $\pm$ 5.4	76.6 $\pm$ 3.1	80.6 $\pm$ 5.4	82.3 $\pm$ 4.7	77.8 $\pm$ 4.1
Time 70-79% HRmax (s)	34.1 $\pm$ 8.8	26.1 $\pm$ 14.6	33.3 $\pm$ 14.0	23.7 $\pm$ 11.1	22.5 $\pm$ 9.6	34.9 $\pm$ 14.2
Time 80-89% HRmax (s)	32.1 $\pm$ 13.3	50.9 $\pm$ 20.2	41.6 $\pm$ 17.0	48.9 $\pm$ 14.8	46.3 $\pm$ 16.3	44.9 $\pm$ 18.4
Time 90-100% HRmax (s)	2.4 $\pm$ 3.3	11.2 $\pm$ 22.5	2.8 $\pm$ 5.3	10.6 $\pm$ 22.6	20.0 $\pm$ 24.7	3.1 $\pm$ 5.2
RPE (0-10)	7.1 $\pm$ 0.8	5.9 $\pm$ 0.7	6.1 $\pm$ 1.0	7.8 $\pm$ 0.9	7.1 $\pm$ 1.1	5.7 $\pm$ 0.9

Pitch sizes: Small = 75 m²·player⁻¹ (46×18 m); Medium = 100 m²·player⁻¹ (55×20 m); Large = 150 m²·player⁻¹ (66×25 m). **Work-to-rest ratios:** 1:1 = 4 min work:4 min rest; 1:0.5 = 4 min work:2 min rest. HRmax; peak heart rate during the bout, HRmean; mean heart rate during the bout, RPE; rating of perceived exertion (Borg CR-10). Values are Mean ± SD, n = 18.

External load responses are presented in Table 3. Total distance covered increased with pitch size at both ratios; the small pitch produced markedly less distance (1508.6±212.6 to 1546.1±248.3 m) than the medium (2004.9±208.2 to 2158.9±236.3 m) and large pitches (2065.6±145.3 to 2185.0±265.2 m). High-speed running and sprint distances were minimal on the small pitch regardless of ratio (≤5.9±12.5 m and 0.0 m, respectively) and were greatest on the large pitch at the 1:1 ratio (28.4±28.5 m high-speed running). Peak running speed and the number of accelerations and decelerations followed a broadly similar pattern, with the lowest values recorded on the small pitch and the highest on the medium or large pitch depending on the variable and ratio.

Table 3. External-Load Responses of the Fixed-Area Transition SSG.

Variable	Large 1:1	Medium 1:1	Small 1:1	Large 1:0.5	Medium 1:0.5	Small 1:0.5
Total Distance (m)	2185.0±265.2	2158.9±236.3	1508.6±212.6	2065.6±145.3	2004.9±208.2	1546.1±248.3
High-Speed Running (m)	28.4±28.5	18.0±17.3	2.8±5.5	11.2±18.9	7.5±16.1	5.9±12.5
Sprint Distance (m)	1.4±2.8	0.0±0.0	0.0±0.0	0.7±2.1	0.7±1.6	0.0±0.0
Peak Speed (m·s ⁻¹)	6.2±0.6	5.9±0.6	5.1±0.6	5.6±0.6	5.6±0.8	5.1±0.7
No. of Accelerations	17.8±4.7	23.9±7.1	12.6±5.8	18.9±4.5	21.8±6.8	14.2±5.8
No. of Decelerations	16.4±8.4	23.2±9.6	12.4±5.2	20.2±7.5	21.2±9.7	14.7±7.5

Pitch sizes and ratios as defined in Table 2. Values are Mean ± SD, n = 18.

The parent three-way repeated-measures ANOVA (Pitch Size × Format × Ratio) revealed a significant three-way interaction for most internal and external load variables (Table 4), indicating that the influence of pitch size and work-to-rest ratio on internal and external load was not uniform across the fixed- and variable-area transition formats and supporting separate consideration of the fixed-area format.

Table 4. Pitch Size × Format × Work-to-Rest Ratio Interaction (Three-Way Repeated-Measures ANOVA).

Variable	F	P	η ² p
HRmax	10.01	<.001***	0.37
%HRmax	10.26	<.001***	0.38
HRmean	9.35	<.001***	0.35
%HRmean	10.10	<.001***	0.37
Time 70-79% HRmax	10.16	<.001***	0.37
Time 80-89% HRmax	9.12	<.001***	0.35
Time 90-100% HRmax	1.98	.153	0.10
RPE	7.29	.002**	0.30
Total Distance	4.08	.026*	0.19
High-Speed Running	7.97	.001**	0.32
Sprint Distance	0.19	.830	0.01
Peak Speed	0.59	.561	0.03
No. of Accelerations	7.73	.002**	0.31
No. of Decelerations	8.34	.001**	0.33

Repeated-measures ANOVA degrees of freedom: Pitch Size = 2,34; Format = 1,17; Ratio = 1,17; Pitch Size × Format × Ratio interaction = 2,34. η²p; partial eta-squared. * P<.05, ** P<.01, *** P<.001.

DISCUSSION

The purpose of this study was to describe the acute internal and external load responses of a fixed-area transition small-sided game across 3 pitch sizes and 2 work-to-rest ratios. The primary findings were that: (a) total distance, high-speed running, and the number of accelerations/decelerations increased with pitch size and were consistently lowest on the small pitch; (b) relative cardiovascular strain (%HRmean, RPE) did not increase monotonically with pitch size but instead peaked on the medium pitch at both ratios; and (c) shortening the recovery interval from 1:1 to 1:0.5 raised RPE on the medium and large pitches but not on the small pitch.

Pitch Size and External Load

The positive relationship observed here between pitch size and total distance, high-speed running, and sprint distance is consistent with the broader SSG literature, in which increasing the relative playing area per player systematically increases the space available for players to exploit high-speed running and sprinting (4,23,24). Casamichana and Castellano (4) and Rampinini et al. (24) similarly reported that larger pitches elevate external load markers because players must cover greater distances to support possession and press opponents. The very low high-speed running and sprint distances recorded on the small pitch in the present fixed-area format (≤ 5.9 m and 0.0 m, respectively) likely reflect the geometric ceiling imposed by $75 \text{ m}^2 \cdot \text{player}^{-1}$, which leaves little room for players to reach high running speeds regardless of the work-to-rest ratio applied (5,10).

Pitch Size and Internal Load

In contrast to the monotonic pattern observed for external load, relative HR and RPE responses peaked on the medium rather than the small pitch. This finding diverges from the frequently reported trend that smaller pitches maximize relative cardiovascular strain because of reduced recovery time between actions (14,24). One plausible explanation is that the fixed-area transition structure used here requiring players to repeatedly switch between attacking and defending roles supported by floating players may impose a distinct internal load profile from the possession-only or unconstrained SSGs on which the small pitch intensity relationship is typically based (1,11). On the smallest pitch, the very limited space may have constrained players to lower velocity, technical/tactical actions with brief recovery pauses built into ball circulation, moderating the cardiovascular strain relative to the medium pitch, where players retained enough space to sustain continuous moderate to high intensity running typical of transition play (18). This interpretation is consistent with the significant Pitch Size $\times$ Format $\times$ Ratio interactions observed for HRmean and %HRmean (Table 4), which indicate that the fixed-area format's HR response to pitch size differs from that of the variable-area format tested in the parent project.

Work-to-Rest Ratio

Shortening the recovery interval from 4 min (ratio 1:1) to 2 min (ratio 1:0.5) increased RPE on the medium and large pitches, in line with the established principle that reducing recovery relative to work duration elevates perceived and cardiovascular strain in intermittent exercise (9,16,19,20). The absence of this effect on the small pitch where RPE was, if anything, numerically lower at the shorter recovery ratio may reflect a self-regulation or pacing behavior: because space (rather than recovery time) was already the binding constraint on the small pitch, players may not have been able to further raise their work rate even when given less recovery, consistent with the very small and non-significant Pitch Size $\times$ Format $\times$ Ratio

interaction observed for peak speed and sprint distance (Table 4). Similar dissociations between prescribed training-density manipulations and their realized physiological effect have been reported when pitch dimensions constrain the movement repertoire available to players (25).

Practical Applications

For coaches using fixed-area transition SSGs, the present data suggest that pitch size and work-to-rest ratio can be manipulated somewhat independently to target different training goals. Medium and large pitches, particularly under the shorter 1:0.5 recovery ratio, elicited the highest cardiovascular and perceptual load and are therefore candidates for aerobic conditioning-oriented sessions (12,13,26). The small pitch produced the lowest external load and a comparatively stable internal load across ratios, making it more suitable for technical and tactical rehearsal of transition play at a controlled physiological cost (6). Because relative cardiovascular strain did not simply track pitch size, coaches should not assume that reducing pitch size alone will maximize the aerobic stimulus of a fixed-area transition SSG; monitoring actual HR and RPE responses, rather than relying on pitch size as a proxy for intensity, remains advisable (17).

Limitations in this Study

Several limitations should be considered. First, because pitch size, transition format, and work-to-rest ratio were manipulated jointly in the parent project, the inferential statistics reported here (Table 4) derive from a three-way model that also included the variable area format; a dedicated two-way (Pitch Size × Ratio) analysis restricted to the fixed-area format alone was not available for this study and is recommended for future work, ideally with a larger sample to preserve statistical power (7,15). Second, the load response comparisons in Tables 1–4 are based on the 18 players occupying the fixed 3 a-side teams; because the four floating attacking support players fulfilled a different tactical role in every trial, quantifying their individual internal and external load responses was beyond the scope of this analysis and is recommended for future work. Third, findings are specific to a 3v3v3(+floaters) fixed-area transition format and a single competitive level, and may not generalize to other formats, player numbers, or competition standards (1,14).

CONCLUSIONS

Within a fixed-area transition small-sided game format, pitch size and work-to-rest ratio influenced internal and external load markers in distinct, only partially overlapping ways. External load total distance, high-speed running, and the number of acceleration/deceleration scaled consistently with pitch size; whereas, relative cardiovascular strain (%HRmean, RPE) peaked on the medium pitch rather than increasing monotonically as pitch size decreased. Shortening the recovery interval (1:0.5 vs. 1:1) increased perceived exertion on the medium and large pitches but not on the small pitch. These results contribute to exercise physiology by showing that, in a transition structured SSG that does not change playing area, pitch size and work-to-rest ratio should be treated as separate, non-interchangeable training levers rather than as redundant ways of increasing intensity, allowing coaches to prescribe external load and internal load stimuli more precisely within this specific training format.

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Effect of Sport Stacking Training on Working Memory Sequencing in E-Sport Players: A Randomized Trial

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ABSTRACT

Phonthee S, Jansupom C, Khongrassame M, Srisaphonphusitti, L, Kusump S, Kanpetta Y, Hiruntrakul A. Effect of Sport Stacking Training on Working Memory Sequencing in E-Sport Players: A Randomized Trial. E-sports performance necessitates high levels of perception, decision-making, and motor execution. These abilities rely heavily on working memory (WM) and executive functions, specifically the capacity to maintain, manipulate, and sequence information. The purpose of this study was to investigate the effects of stacking training on WM sequencing performance among E-sport players compared to conventional training methods. Twenty E-sport players were randomly assigned to either the Stacking Group (SG) or the Control Group (CG), which continued with their standard E-sports training regimen. Both Groups participated in 12 intervention sessions over 4 weeks (3 sessions/week, 30 minutes/session). WM sequencing performance, including storage (ascending order task) and manipulation (descending order task), was measured at pre-test and post-test. Within-group analysis (paired *t*-tests) revealed that the SG showed statistically significant improvements in both the ascending order (pre: mean = 5.90 ± 0.74 , post: mean = 7.40 ± 0.97 ; $P < 0.001$) and descending order tasks (pre: mean = 2.30 ± 0.82 , post: mean = 3.00 ± 0.00 ; $P = 0.025$); whereas, the CG showed no significant changes. Although between-group comparisons revealed no statistically significant differences in change scores for either task (ascending: $P = 0.061$; descending: $P = 1.000$), a trend toward superior improvement in the SG was noted for the ascending task. Although a 4-week sport stacking training effectively enhanced WM within the Stacking Group, it did not demonstrate superiority over conventional E-sports training. Nevertheless, sport stacking serves as a viable, low-cost motor-cognitive tool that can be integrated into E-sports training to reinforce cognitive performance.

Key words: Cup Stacking, Electronic Sports, Motor-Cognitive Training, Motor Skills, Working Memory

INTRODUCTION

Electronic sports (E-sports) have evolved into a high-performance domain that places intense, real-time cognitive demands on players, including perception, attention, memory, planning, and decision-making (4,12). Players must continuously monitor multiple information streams, update mental representations of dynamic game states, and plan and execute multi-step action sequences under severe time pressure. These constant decision-making situations require robust problem-solving skills and cognitive flexibility. In neuropsychology, these cognitive abilities are categorized as executive functions (EFs), that is, a set of mental processes necessary for the cognitive control of behavior: working memory (WM), cognitive flexibility, and inhibitory control (26). Research has demonstrated that the higher the EFs of an athlete, the more effective the player (2,3,18,22,26). Notably, WM is not merely temporary storage and, in fact, its central executive component supports the active manipulation and ordered sequencing of items required for complex, goal-directed behavior (22,26). In E-sports, WM sequencing is crucial for tracking opponent cooldowns, objective timers, and multi-step tactical execution. Consequently, interventions targeting WM sequencing may serve as a catalyst for enhanced in-game performance (4,24,26).

Cognitive training studies and research on video-game play indicate that certain types of practice can improve attention, visuospatial processing, and some WM components (8,27,29). However, typical laboratory cognitive training paradigms (e.g., adaptive N-back tasks) often isolate cognitive operations from motor demands and may show limited transfer to ecologically valid tasks involving sensorimotor coordination (17). Conversely, combined motor-cognitive training interventions, such as those that integrate physical actions with cognitive challenge have demonstrated greater potential for producing transferable gains in cognition compared with single-domain training in a variety of populations (20,32). For E-sports players, whose performance is predicated on the tight coupling of cognitive processing and manual dexterity, such integrated approaches are particularly promising.

Sport stacking, also known as cup stacking, is a structured activity that inherently couples rapid bilateral hand movements with visuospatial sequencing and timing constraints. During stacking, the participants must plan and execute ordered sequences of hand actions while maintaining an accurate representation of spatial and temporal relationships among cups (14). These demands overlap substantially with the sequencing and visuomotor integration requirements of various E-sports tasks. Previous research has reported numerous benefits of sport stacking, including improvements in hand-eye coordination in school-aged children and small adult samples (16), reaction time (21), bilateral coordination (25), and dual hemispheric brain activity (15). However, despite its potential as a motor-cognitive training modality, the efficacy of sport stacking in enhancing high-level WM sequencing among E-sports player cohorts remains unexplored.

Given that E-sports players often begin with high baseline cognitive and sensorimotor skills, it is unclear whether adding a structured motor-cognitive program like sport stacking will produce measurable gains in WM sequencing beyond routine game practice. The present study investigated whether a 4-week sport stacking intervention can provide incremental gains in WM sequencing beyond routine practice in university E-sports players, using sequencing-sensitive cognitive tests (e.g., Number Sequencing and a serial-order N-back variant). The findings will empirically establish the efficacy of integrating non-gaming, motor-cognitive training into

established E-sports players training protocols and potentially serve as empirical confirmation of stacking's benefits for competitive cognitive performance.

METHODS

Study design

This study was a randomized controlled trial (RCT) with pre- and post-test measurements. The participants were randomly allocated into 2 parallel groups using computer-generated simple randomization: a Stacking Group (SG) and a Control Group (CG). The SG received cup-stacking training while the CG followed conventional E-sports training. Both interventions were delivered over 4 weeks (Figure 1).

The study protocol was approved by the Human Ethics Committee of Surin Rajabhat University. The research was conducted in accordance with the Declaration of Helsinki, The Belmont Report, CIOMS guidelines, and ICH-GCP. Ethics approval number: HE 672067.

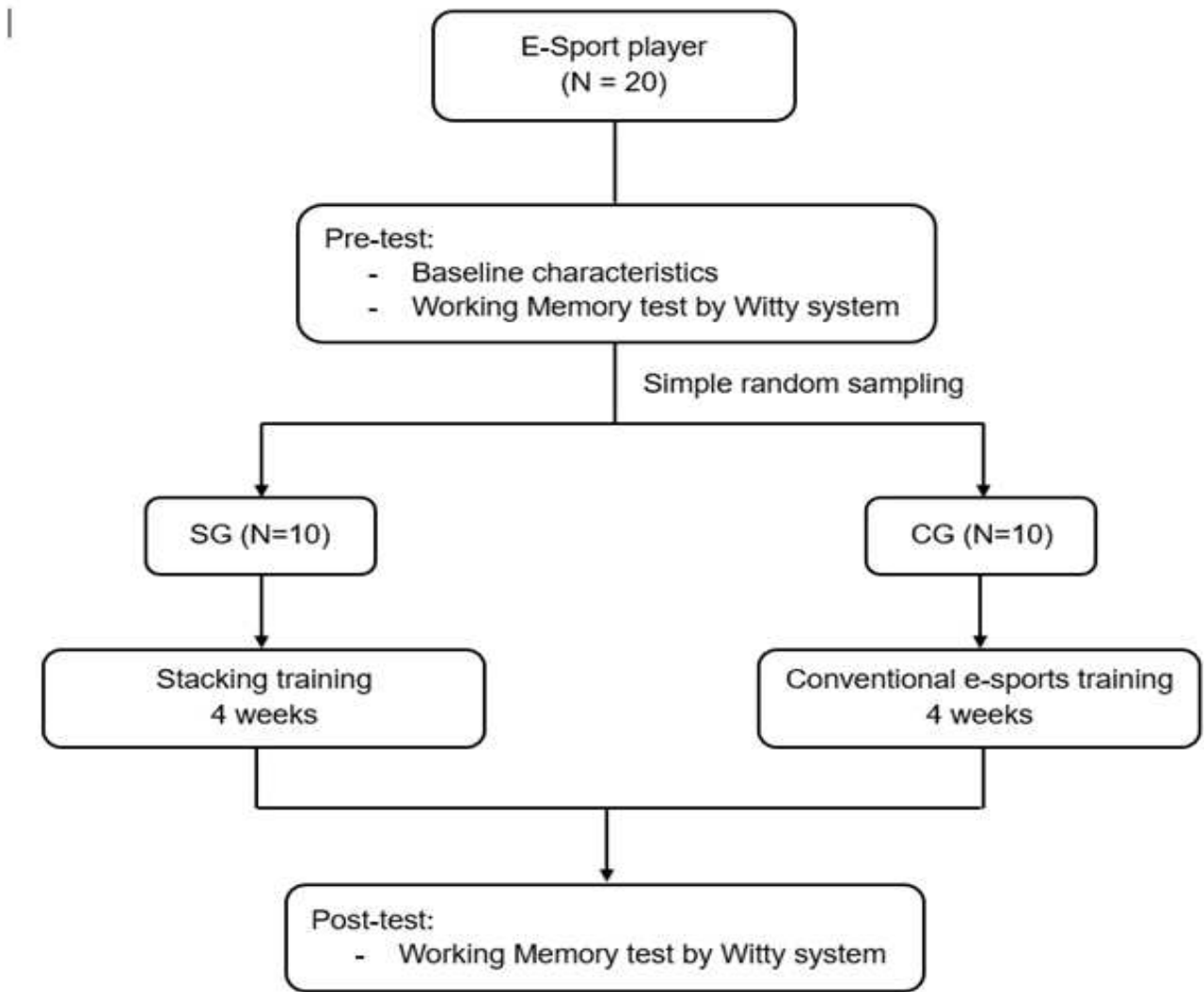


Figure 1. Flow Chart of the Study (SG = Stacking Group, CG = Control Group).

Subjects

Twenty (N = 20) E-sports players (age 18-25 years) from Surin Rajabhat University participated. The **Inclusion Criteria** were age 18-25 years and at least 1 year of competitive experience. Prior to participation all the players completed the Physical Activity Readiness Questionnaire (PAR-Q), and they reported no prior experience with the specific stacking training used in this study. The **Exclusion Criteria** were: (a) visual impairment that would interfere with the tasks; (b) clinical depression; (c) neurologic, psychiatric, orthopedic, or cardiovascular conditions that could affect outcomes; and (d) current use of medications likely to influence cognitive and/or motor performance.

Sample size was calculated using G*Power (version 3.1.9.2) for an independent *t*-test, based on a previous study (32). Using $\alpha = 0.05$, power = 0.80, and estimated effect size $d = 1.44$, the minimum required sample was 14 participants (7 participants per group). To allow for attrition, the target sample size was increased by 20% to 20 participants. Twenty eligible participants were randomized to the 2 Groups (SG, $n = 10$; CG, $n = 10$) using a simple randomization sequence. The sequence was generated by a researcher not involved in outcome assessment. Allocation concealment was maintained using sealed opaque envelopes.

Procedures

All the participants provided informed consent and were notified of their right to withdraw from the study at any time. They also completed the PAR-Q to ensure their readiness for physical activity. Baseline assessments, including WM performance, were conducted prior to the intervention. Post-training assessments were conducted within 3 days after the final training session. Assessors were blinded to Group allocation. WM was assessed using the Witty SEM system (Microgate, Italy) (5), a device for reaction-time and cognitive-motor tasks. A Modified Sequencing Task, adapted from previously described methods (5,33), was used to dissociate WM storage and manipulation components (1). The task is conceptually equivalent to ascending order condition and descending order condition.

Stimuli were presented with the Witty system using the Juggle Factor function. Two sequencing conditions were administered:

- *Ascending Order Condition* (Digit span forward/Storage): Lights were presented in ascending numerical order (e.g., Light No. 1, 2, 3 ...) (Figure 2A). The participants were instructed to recall and to reproduce the sequence by tapping the lights in ascending order (from lowest to highest). This condition assessed WM storage capacity.
- *Descending Order Condition* (Digit span backward/Manipulation): Lights were presented in a randomized sequence (e.g., Light No. 4, 2, 6, 1) (Figure 2B). The participants were instructed to mentally reorder the remembered sequence and tap the lights from highest to lowest. This condition assessed WM manipulation and central executive processes.

Each condition was comprised of 10 trials. Sequence length ("span") increased systematically across the trials. Scoring was based on the number of trials reproduced exactly in the correct order (1 point per perfectly sequenced trial).

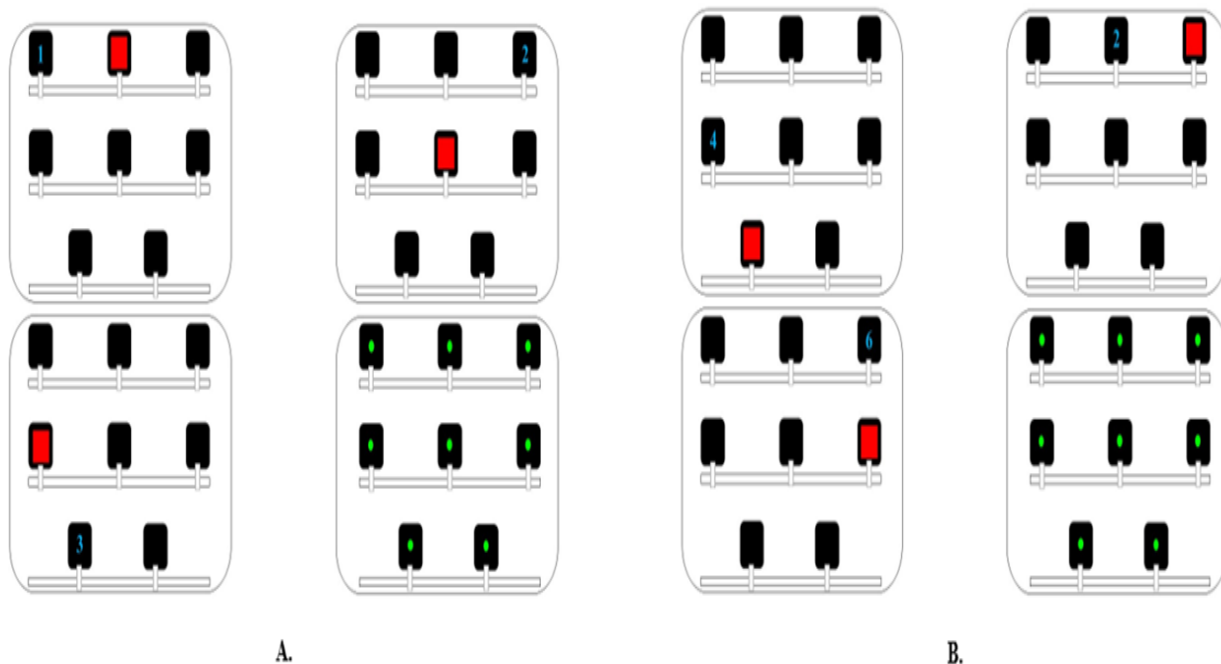
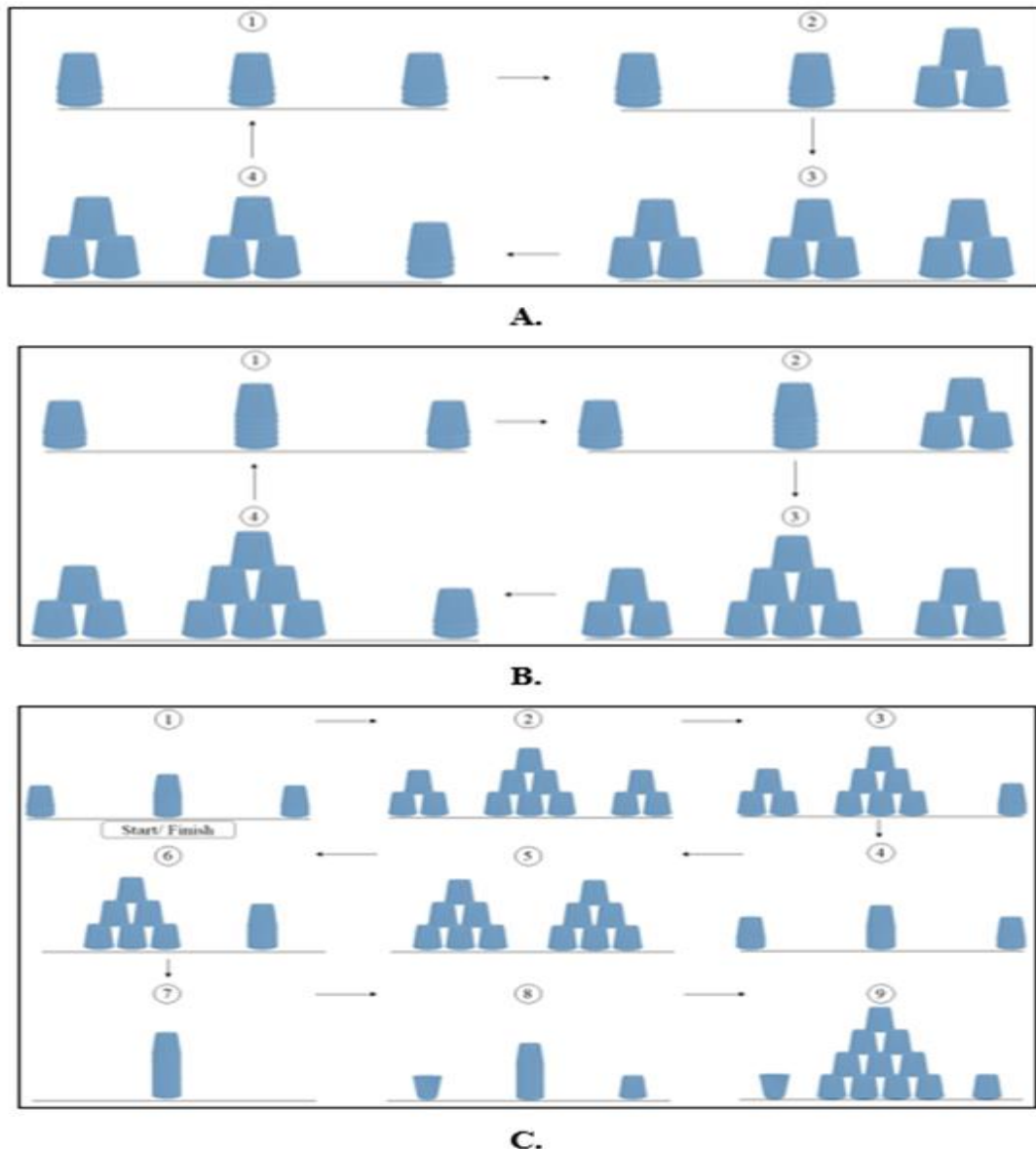


Figure 2. A: *Ascending Order Condition*
B: *Descending Order Condition*

Intervention

Both Groups received a total of 12 training sessions over 4 weeks (3 sessions per week, 30 minutes per session) by a trainer. Outside of these scheduled sessions, the participants did not perform any additional physical training. The training protocols for each Group are detailed below:

- **SG:** The participants completed a structured cup stacking program based on established protocols (24). Each 30-minute session was divided into three 10-minute segments focusing on specific stacking patterns: *Segment 1:* 3-3-3 pattern (Figure 3A), *Segment 2:* 3-6-3 pattern (Figure 3B), and *Segment 3:* Full cup stacking pattern (Figure 3C).
- **CG:** The participants continued their usual E-sports training program, matched to the SG for session frequency, duration, and timing (12 sessions over 4 weeks; 3 sessions/week; 30 minutes/session).



Statistical Analysis

Data Availability

The data associated with the paper are not publicly available but are available from the corresponding author on reasonable request. The data are located in controlled data storage at Khon Kaen University.

RESULTS

Twenty E-sports players were divided into 2 Groups, the Stacking Group (SG) and the Control Group (CG). The mean age was 20.80 ± 1.50 years for the SG and 19.50 ± 1.58 years for the CG. There were no significant differences between the Groups in their gaming experience (4.16 ± 1.51 years and 3.97 ± 1.63 years, respectively) and WM performance. The demographic characteristics of both Groups are shown in Table 1.

Table 1. Demographic Characteristics of SG and CG.

Variables	SG (n = 10)	CG (n = 10)	P value
Age (yrs)	20.80 ± 1.55	19.50 ± 1.58	0.080
Experience (yrs)	4.16 ± 1.51	3.97 ± 1.63	0.790
Height (cm)	173.40 ± 6.45	173.90 ± 5.70	0.856
Weight (kg)	65.54 ± 12.01	68.81 ± 12.69	0.561
BMI (kg/m ²)	21.65 ± 3.08	22.76 ± 4.01	0.499
HR rest (bpm)	76.40 ± 12.73	79.70 ± 12.96	0.573
Syst BP (mmHg)	116.40 ± 16.59	116.60 ± 7.35	0.973
Dias BP (mmHg)	68.10 ± 6.90	70.40 ± 7.68	0.490
Ascending Order	5.90 ± 0.74	6.60 ± 0.97	0.085
Descending Order	2.30 ± 0.82	2.70 ± 0.48	0.201

Values are presented as number only or mean $\pm$ standard deviation, P values were calculated with independent samples *t*-test, **SG** = Stacking Group, **CG** = Control Group, **BMI** = Body Mass Index, **HR rest** = Resting heart rate, **Sys BP** = Systolic Blood Pressure, **Dias BP** = Diastolic Blood Pressure

According to Table 2, the SG showed a significant improvement in both the ascending order condition (**Pre**: 5.90 ± 0.74 ; **Post**: 7.40 ± 0.97 ; $P < 0.001$) and the descending order condition (**Pre**: 2.30 ± 0.82 ; **Post**: 3.00 ± 0.00 ; $P = 0.025$). Conversely, the CG showed no significant change in either the ascending order ($P = 0.687$) or the descending order ($P = 0.081$) conditions over the 4-week period. Regarding the magnitude of change (improvement scores) between 2 Groups, the independent samples *t*-test revealed a near-significant trend in the ascending order condition ($P = 0.061$), suggesting a greater improvement in the SG compared to the CG. However, no statistically significant difference was found for the change scores in the descending order condition ($P = 1.000$).

Table 2. Comparisons of Performance on the Working Memory Sequencing Task (Ascending Order and Descending Order Conditions) Between the SG and the CG.

Variables	Groups	Pre-test	Post-test	P value ^a	P value ^b
Ascending Order	SG	5.90 ± 0.74	7.40 ± 0.97	<0.001*	0.061
	CG	6.60 ± 0.97	6.70 ± 0.48	0.687	
Descending Order	SG	2.30 ± 0.82	3.00 ± 0.00	0.025*	1.000
	CG	2.70 ± 0.48	3.00 ± 0.00	0.081	

Values are presented as mean ± standard deviation

^aP values were calculated with paired samples *t*-test

^bP values were calculated with independent samples *t*-test

*Significant P value was < 0.05

SG = Stacking Group, **CG** = Control Group

DISCUSSION

The purpose of this study was to investigate the efficacy of a 4-week cup stacking training versus conventional E-sports training on WM sequencing in E-sports players. The most critical finding indicates that the stacking training significantly improved WM performance within the SG. Statistically significant gains were observed in both WM storage capacity (Ascending Order scores improved from 5.90 ± 0.74 to 7.40 ± 0.97; $P < 0.001$) and WM manipulation, which reflects the strengthening of the central executive (8,22) (Descending Order improved from 2.30 ± 0.82 to 3.00 ± 0.00; $p = 0.025$). The CG, conversely, showed no similar improvement (Table 2).

The results underscore the cognitive benefits inherent in this specialized training modality. Sports stacking is recognized as a dynamic sport that demands significant speed, accuracy, and sensorimotor coordination, which theoretically requires the recruitment of higher-order cognitive processes. Previous studies have consistently linked such dynamic, skilled motor activities to the development of cognitive abilities, particularly those associated with EFs and rapid information processing (6,8). While direct neurological changes were not measured in this study, engaging in sports stacking, a complex sequential motor task is suggested in the literature to activate the prefrontal cortex, the primary region governing core EFs (8,10,34). Such engagement may support 'Whole-Brain' functions, including processing speed, sequencing, and inter-hemispheric coordination (32).

Furthermore, systematic cup stacking training has specifically been shown to be an effective method for enhancing neuromuscular coordination, hand-eye coordination, and high-level motor skills in players (10,32,34). Throughout the 4-week intervention, the participants in the SG demonstrated progressive improvements in stacking accuracy and fluid movement sequencing. While individual learning rates varied with some participants achieving consistent patterns more rapidly than others of which the collective trend showed enhanced motor-cognitive integration. These improvements are hypothesized to be associated with the

strengthening of connections between brain networks and may contribute to the development of cognitive reserve over the long term (9,30). Specifically, the practice is hypothesized to improve WM by strengthening the central executive, that is, the component responsible for the ability to control and organize information (10). Our findings support this, showing that the cup stacking training led to an increase in WM performance in both ascending ($P < 0.001$) and descending order ($P < 0.050$, Table 2).

However, despite the improvements within the SG, the statistical analysis revealed no significant difference when comparing the outcomes between the 2 Groups. However, a near-significant trend for Group differences was observed in the Ascending Order scores ($P = 0.061$, Table 2). Historically, WM sequencing tasks have been strongly correlated with advanced mental manipulation and planning skills (22). In this test, the participants were required not only to recall numbers (storage), but also to perform manipulation by touching the corresponding lights in the numerical sequence, which is a process that relies heavily on the WM sequencing targeted by the stacking intervention.

The improvement observed across both WM conditions directly addresses critical cognitive demands placed upon E-sports professionals. Enhancement in ascending WM supports foundational skills required in competitive gaming, such as game tracking, pattern recognition, and maintaining high situational awareness (12,13), including the essential ability to track cooldowns and enemy positions in dynamic environments (22). Furthermore, descending WM capacity is particularly vital for elite e-sports performance. The central executive responsible for information manipulation (2) is the foundation for complex strategic operations that includes real-time strategy adjustment, multitasking and inhibition, and rapid risk assessment, all of which characterize high-level competitive gaming (4,11).

The four-week cup stacking training used in this study represents an intensive, targeted training method that demands motor-cognitive integration. This rigorous approach is suggested to support the development of automaticity in movement sequencing following the prescribed stacking patterns (23) (Figure 3A-C). While players execute rapid hand movements, the brain must continuously monitor and engage in the sequencing and planning of complex configurations. Throughout the training, although individual learning curves and the mastery of stacking accuracy varied among players, the overall intervention functions as a highly structured, rapid-paced external sequencing task that mirrors the internal cognitive demands of E-sports. The continuous forced planning and execution of these patterns may train the EFs to more efficiently manage a rapid chain of events under time pressure. The findings, therefore, suggest that specialized motor-cognitive training like sports stacking could serve as an effective intervention to prepare e-sports players for the high cognitive load inherent in their profession (14,16,32).

Despite these improvements within the SG, the statistical analysis revealed no significant difference when comparing the outcomes between the 2 Groups. However, a near-significant trend for Group differences was observed in the Ascending Order scores ($P = 0.061$, Table 2). The lack of statistical significance between the Groups may be attributed to the 4-weeks intervention period that included focused game play for both Groups that likely contributed to cognitive performance gains across the board, which is a finding consistent with the literature showing that game play itself can enhance cognitive abilities (31). Furthermore, previous research on cognitive training suggests that demonstrating clear superiority over active control groups often require a longer, sustained training period, typically 8 to 12 weeks (28,34). Thus,

the 4-week duration, although intensive, may represent an insufficient training dose to clearly surpass the cognitive benefits inherent in the Control Group's activities. Additionally, the observed variability in individual learning rates and initial stacking accuracy among participants may have further diluted the between-group statistical power within this timeframe. Future studies with extended durations may be necessary to fully capture the differential impact of cup stacking compared to standard gaming practice.

Furthermore, a critical limitation was identified concerning a ceiling effect in the descending order condition. Post-training analysis revealed that all the participants achieved the maximum possible score (post-test 3.00 ± 0.00 in both Groups). This lack of score variance indicates that the WM sequencing task, as implemented through the Witty System, may have lacked the necessary psychometric depth and sensitivity to differentiate between higher-level cognitive abilities in the specific population. Consequently, the descending conditions could not adequately discriminate between the 2 Groups, as the participants reached their maximum measurable performance. This limitation has likely masked any potential differential effects between the SG and the CG activities. Given that elite-level performance often hinges on minute differences in processing speed and accuracy, the current assessment tool may not have been sufficiently challenging to capture these nuances. Future studies should utilize more cognitively demanding or adaptive WM assessment tools, such as the Operation Span Task (OSPAN) or N-Back designs, to more accurately measure and compare the upper limits of cognitive capacity in elite athletes (6).

CONCLUSIONS

This study investigated the effects of a 4-week sports stacking training on working memory performance of E-sports players compared to a conventional E-sports training program. The primary finding was a significant improvement within-group in both ascending ($P < 0.001$) and descending ($P < 0.050$) WM conditions for the SG (Table 2). Although no statistically significant difference was found between the 2 Groups, which was potentially due to the intervention duration and the active nature of the CG, the robust improvements within the SG suggest that sports stacking is a viable, low-cost, and non-gaming-specific motor-cognitive training modality. This intervention can be readily integrated into E-sports training protocols to challenge and potentially enhance crucial cognitive functions, specifically sequencing and information manipulation. Despite individual variations in learning rates, sports stacking serves as a valuable supplemental tool for cognitive performance optimization in competitive gaming professionals.

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The Effect of Dual-Task Fitness Programming on the Cognitive Functioning of Adults Over Age 50

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ABSTRACT

Radzynski G, Radzynski S. The Effect of Dual-Task Fitness Programming on the Cognitive Functioning of Adults Over Age 50. The purpose of this study was to determine whether a 12-week Dual Task Fitness Program (DTFP) that integrated cognitive challenges with aerobic and resistance-based exercise produced greater cognitive improvements than a Traditional Exercise Program (TEP) in adults over age 50. The participants completed pre- and post-intervention cognitive testing with the Creyos Health Cognitive Assessment. The DTFP Group completed functional exercise sessions that incorporated cognitive tasks using SmartFit Boards, SmartFit Pods, and group-based brain-building activities; whereas, the TEP Group completed physically similar exercise sessions without cognitive tasks. The final DTFP Group included 23 participants (62.3 ± 7.53 yrs; 82.7% female), and the final TEP Group included 18 participants (59.7 ± 6.14 yrs; 83.3% female). The DTFP Group improved across all 9 cognitive domains, with significant within-group improvements in verbal short-term memory ($P = 0.030$) and response inhibition ($P = 0.001$). Between-group analyses showed significant post-test advantages for the DTFP in verbal short-term memory ($P = 0.020$) and visual-spatial working memory ($P = 0.031$). These findings suggest that combining cognitive stimulation with structured exercise may provide broader cognitive benefits than exercise alone and support DTFP as a feasible nonpharmacological strategy for promoting cognitive health in adults over age 50.

Key Words: Cognitive Aging, Dual-Task Training, Executive Function, Exercise Intervention

INTRODUCTION

Age-related cognitive decline has emerged as a major public health concern as the population of older adults continues to grow. By 2030, adults aged 65 years and older are expected to comprise approximately 20% of the U.S. population (13). Although some decline in cognitive functioning is associated with aging, deterioration in memory, executive function, attention, and processing speed is not considered an inevitable consequence of growing older (9,11). Cognitive impairment ranges from mild deficits to severe neurodegenerative disorders such as Alzheimer's disease, which accounts for approximately 60-80% of dementia cases and substantially reduces quality of life while increasing healthcare costs and caregiver burden (11). Consequently, identifying effective, non-pharmacological strategies to preserve cognitive health has become a public health priority (13).

Regular physical activity has consistently been associated with improved cognitive performance and a reduced risk of cognitive impairment among older adults (2,4). Exercise has been shown to enhance memory, executive function, and attention through mechanisms including increased cerebral blood flow, neurogenesis, synaptic plasticity, and elevated brain-derived neurotrophic factor (BDNF) (4,13). Similarly, cognitive training interventions have demonstrated positive effects on memory, attention, and problem-solving abilities in the aging populations (1,6). While both approaches independently improve cognitive functioning, relatively little research has examined whether integrating cognitive challenges into structured physical exercise produces greater benefits than exercise alone.

Existing studies have largely investigated physical exercise and cognitive training as separate interventions, leaving an important gap in understanding their combined or potentially synergistic effects (10). Furthermore, limited evidence exists regarding the optimal integration of cognitive and physical activities to maximize cognitive outcomes in adults over the age of 50 (5). As cognitive decline often accelerates during the fifth and sixth decades of life, interventions targeting this age group may offer significant opportunities to preserve cognitive function before substantial impairment develops (11).

The purpose of this study was to evaluate the effects of a Cognitive Activity Fitness Programming (CAFP) intervention that integrates cognitive tasks with aerobic and resistance exercise on cognitive functioning in adults over the age of 50. Cognitive outcomes, measured using the Croyos Cognitive Assessment, were compared with those of participants completing a traditional functional fitness program without embedded cognitive activities. By examining whether combining cognitive and physical exercise produces greater improvements than physical exercise alone, this study contributes to the growing evidence supporting multidomain interventions for healthy aging. The findings have the potential to inform evidence-based exercise programming, promote cognitive resilience, and improve quality of life while reducing the societal burden associated with age-related cognitive decline.

METHODS

Subjects

The participants were adults over the age of 50. They were recruited from the local fitness centers, email advertisements, and Facebook between January and April 2024. A total of 52 individuals expressed interest, however, only 50 met initial screening criteria, and 49 adults completed the baseline assessments. The participants were randomly assigned in a 1:1 ratio to either the Dual Task Fitness Program (DTFP) Group or the Traditional Exercise Program (TEP) Group using block randomization stratified by sex. The final analytic sample included 41 participants who completed the intervention.

The Inclusion Criteria required that the participants reported good health to be cleared for moderate-intensity exercise, that they had no diagnosis of dementia, mild cognitive impairment, Parkinson disease, or stroke, and they were free of uncontrolled cardiovascular or metabolic disease, had normal or corrected-to-normal vision and hearing sufficient for computerized cognitive testing, and were not participating in structured cognitive training or dual-task exercise programming. The Exclusion Criteria included unstable angina, recent cardiac events, uncontrolled hypertension (greater than 160/100 mmHg), major orthopedic limitations, recent psychiatric hospitalization, or neurological disorders known to affect cognitive testing.

The DTFP Group began with 25 participants and retained 23 participants. The TEP Group began with 24 participants and retained 18 participants. The 2 Groups were similar in age and sex distribution (Table 1). The study was approved by the University Institutional Review Board, and all the participants provided written informed consent.

Table 1. Descriptive Data of the Subjects.

Group	n	Mean Age	SD	Gender (%)
DTFP	23	62.3	7.53	Female - 82.7% Male - 17.3%
TEP	18	59.7	6.14	Female - 83.3% Male - 16.7%

Abbreviations: **DTFP** = Dual Task Fitness Program; **TEP** = Traditional Exercise Program; **SD** = Standard Deviation

Procedures

All the participants completed baseline assessment at Week 0 and post-intervention assessment at Week 12. Cognitive outcomes were measured using the Creyos Health Cognitive Assessment. The participants were instructed to complete testing under standardized conditions in a quiet private room with adequate sleep, minimal distractions, and independent completion. The assessment took approximately 1 hour and the results

were uploaded automatically to the Creyos platform. Before training, each participant completed a baseline health and functional evaluation that included medical history, PAR-Q and fitness questionnaires, anthropometric measurements, an InBody composition scan, push-up and squat tests, a 3-min rower test, and functional movement screening. Physician clearance was obtained when indicated by PAR-Q responses.

Both Groups completed a 12-week intervention consisting of three 60-min sessions each week at Activate Brain and Body in Indianapolis, Indiana. The sessions were supervised by certified exercise professionals trained in the protocol. Attendance was recorded at each session. Both Groups completed similar functional exercise formats and one weekly Flexibility, Mobility, and Relaxation (FMR) session. The distinguishing feature of DTFP was the integration of cognitive-motor tasks during exercise; whereas, TEP excluded SmartFit activities and other cognitive components.

Table 2. Structure of the Dual Task Fitness Program.

Session Type	Component	Description	Duration
Cognitive Circuit Workout	Icebreaker	Group introductions to foster social interaction and engagement.	5 min
	Exercise Demonstration	Instructor demonstrates all exercises for the session.	5 min
	Warm-up	Tailored warm-up based on each participant's functional movement score.	10 min
	Workout Phase	Combined cognitive-motor circuit incorporating cognitive challenges using SmartFit Boards and SmartFit Pods.	30 min
	Brain Builder Group Activity	Cognitive challenge activity using T-Wall Technology.	5 min
	Functional Cooldown	Stretching, foam rolling, and breathing exercises for recovery and relaxation.	5 min
FMR Workout	Breathing Exercise	Breathing exercise designed for relaxation at the start of the session.	5 min
	Foam Rolling	Foam rolling exercises to release muscle tension and improve flexibility.	10 min
	Static Stretching	Static stretching exercises, occasionally augmented with power bands.	10 min
	Functional Movement Exercises	Exercises focused on improving functional movement and mobility.	10 min
	Breathing Cooldown	Breathing exercise to conclude the session.	5 min

Table 3. Structure of the Traditional Exercise Program.

Session Type	Component	Description	Duration
Full Body Training Session	Introduction	Group introductions to foster social interaction and engagement.	5 min
	Exercise Demonstration	Instructor demonstrates all exercises for the session.	5 min
	Warm-up	Tailored warm-up based on each participant's functional movement score.	5 min
	Main Workout	Functional exercises completed without cognitive challenges.	30 min
	Functional Cooldown	Stretching, foam rolling, and breathing exercises for recovery and relaxation.	5-10 min
FMR Workout	Breathing Exercise	Breathing exercise designed for relaxation at the start of the session.	5 min
	Foam Rolling	Foam rolling exercises to release muscle tension and improve flexibility.	10 min
	Static Stretching	Static stretching exercises, occasionally augmented with power bands.	10 min
	Functional Movement Exercises	Exercises focused on improving functional movement and mobility.	10 min
	Breathing Cooldown	Breathing exercise to conclude the session.	5 min

Statistical Analyses

The data were analyzed using IBM SPSS Statistics Version 29. Primary outcomes were Creyos cognitive scores, with emphasis on verbal short-term memory, visual-spatial working memory, and response inhibition. Descriptive statistics were calculated for the participant characteristics and the pre-to-post changes in cognitive domains.

Within-group changes were analyzed using the paired-samples *t*-tests, and between-group post-intervention differences were analyzed using independent-samples *t*-tests. The significance level was set at $\alpha = 0.05$. Effect sizes and confidence intervals were used for interpretive clarity when available. The source manuscript reported *a priori* power target of 60 participants. The final analytic sample included 41 participants, so smaller effects should be interpreted cautiously.

RESULTS

The DTFP Group improved across all 9 cognitive domains. The strongest percentage improvements occurred in response inhibition (+9.88%), verbal reasoning (+8.29%), and episodic memory (+5.11%). Additional gains were observed in verbal short-term memory (+3.95%), working memory (+1.58%), visual-spatial working memory (+1.57%), spatial short-term memory (+0.90%), visual-spatial processing (+0.52%), and deductive reasoning (+0.40%). Improvement rates were also high, with 96% of the DTFP participants improving in response inhibition and 69% improving in verbal short-term memory and working memory.

The TEP Group demonstrated a more variable pattern of cognitive change. The largest improvements were observed in response inhibition (+6.27%), verbal reasoning (+5.18%), episodic memory (+2.42%), working memory (+2.36%), and deductive reasoning (+0.50%). However, TEP declined in spatial short-term memory (-3.42%), verbal short-term memory (-1.84%), and visual-spatial processing (-1.09%).

Within-group analyses showed statistically significant improvements for DTFP in verbal short-term memory ($t = -1.98$, $P = 0.030$) and response inhibition ($t = -5.40$, $P = 0.001$). The remaining DTFP domains showed positive but nonsignificant trends. Within the TEP Group, response inhibition ($P = 0.009$) and spatial short-term memory ($P = 0.037$) improved significantly, while other domains did not reach significance.

Between-group analyses indicated that DTFP significantly outperformed TEP at post-test in verbal short-term memory ($P = 0.020$) and visual-spatial working memory ($P = 0.031$). Other domains did not show significant post-test group differences, although descriptive patterns generally favored DTFP. These results suggest that integrating cognitive challenges into structured exercise produced broader and more consistent cognitive gains than exercise alone.

DISCUSSION

Primary Findings

The purpose of this study was to determine whether Dual Task Fitness Programming (DTFP) produced greater cognitive benefits than a traditional exercise-only program (TEP) in adults over age 50. The findings supported this hypothesis in key cognitive domains. DTFP resulted in significant within-group improvements in verbal short-term memory and response inhibition and produced significant between-group advantages in verbal short-term memory and visual-spatial working memory.

The DTFP Group improved across all 9 cognitive domains; whereas, the TEP Group demonstrated a narrower and less consistent pattern of change. The strongest DTFP gains occurred in response inhibition, verbal reasoning, episodic memory, and verbal short-term memory. These cognitive domains are critical for everyday functioning, including learning new information, following instructions, organizing tasks, and regulating behavior (8,11).

Dual-Task Training Effects

The superior DTFP outcomes may reflect the combined demands of physical movement and cognitive engagement. During DTFP, the participants were required to maintain motor control while responding to changing rules, visual cues, memory demands, and group-based cognitive tasks. This type of training likely engaged attentional switching, working-memory updating, response inhibition, and visual-spatial processing, cognitive processes that have been associated with improved executive functioning in previous multidomain intervention studies (1,4,10).

The significant between-group advantage in visual-spatial working memory is especially relevant because many daily activities require simultaneous navigation, balance, attention, and memory. Similarly, improvements in verbal short-term memory may enhance functional communication and the ability to retain and act upon verbal information. These findings suggest that embedding cognitive challenges within exercise may strengthen cognitive domains not consistently improved through physical exercise alone (4,6).

The present findings are consistent with previous research demonstrating that interventions combining physical exercise with cognitive training often produce greater cognitive benefits than either intervention alone (4,10). The current study extends this literature by demonstrating significant improvements in verbal short-term memory and visual-spatial working memory following a structured dual-task fitness program in adults over age 50.

Exercise-Only Effects

The TEP Group improved significantly in response inhibition and spatial short-term memory, indicating that structured functional exercise can support selected aspects of cognition. These findings are consistent with the broader literature showing that moderate-intensity aerobic and resistance training can improve executive function and cognitive control (3,4,7). However, the TEP Group also declined in several memory-related and visual-spatial domains, suggesting that exercise alone may not provide the same breadth of cognitive stimulus as dual-task training.

Practical Implications

These findings support the incorporation of dual-task elements into community fitness, senior wellness, and rehabilitation programs. Rule-based movement challenges, memory tasks, inhibitory-control drills, and visual-spatial problem-solving activities can be integrated into existing strength, balance, and aerobic exercise programs without replacing physical training. This multidomain approach may be particularly valuable for adults in midlife and later life who seek to preserve cognitive function while improving physical health (4,13).

The use of structured technology such as SmartFit Boards, SmartFit Pods, and T-Wall activities may help standardize cognitive load and facilitate progressive training. However, similar principles can also be implemented using low-technology approaches that require

the participants to remember movement sequences, respond to visual or auditory cues, inhibit incorrect responses, and solve movement-based cognitive challenges.

Limitations and Future Research

Several limitations should be considered when interpreting these findings. The final sample size was modest and may have limited statistical power to detect small-to-moderate between-group differences. The sample consisted of adults able to participate in structured exercise, limiting generalizability to individuals with advanced cognitive impairment, major mobility limitations, or chronic health conditions. In addition, demographic factors such as educational attainment, socioeconomic status, and lifestyle behaviors were not primary variables in the analysis and may have influenced cognitive outcomes.

Future research should examine larger and more diverse populations, evaluate the long-term retention of cognitive improvements, and determine whether cognitive gains translate into measurable improvements in daily functioning. Additional studies should investigate the influence of cognitive task complexity, exercise intensity, intervention duration, and delivery setting on intervention effectiveness. Incorporating neurobiological measures, including neuroimaging, electrophysiological assessments, or biomarkers, may further clarify the mechanisms through which dual-task exercise influences cognitive aging.

CONCLUSIONS

This study provides evidence that Dual Task Fitness Programming is a promising nonpharmacological intervention for supporting cognitive function in adults over age 50. Compared with traditional exercise alone, the DTFP produced broader cognitive improvements and significant advantages in verbal short-term memory and visual-spatial working memory. These findings suggest that integrating cognitive challenges into structured exercise may promote cognitive resilience, functional independence, and quality of life in aging adults. Larger randomized studies are warranted to confirm these findings, determine their long-term durability, and further establish the role of dual-task fitness programming in healthy cognitive aging.

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Developing a Community-Based Thai Traditional Sports Exercise Program for Older Adults: A Participatory Mixed-Methods.

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ABSTRACT

Bussamongkhon P, Kensila U, Thonglong T. Developing a Community-Based Thai Traditional Sports Exercise Program for Older Adults: A Participatory Mixed-Methods. The purpose of this study was to develop a community-based Thai traditional sports exercise program and examine its content validity, feasibility, preliminary effects on health-related physical fitness, active aging, and implementation acceptability among community-dwelling older adults. A four-phase participatory mixed-methods study was conducted in Udon Thani Province, Thailand. Phase 1 used document review, in-depth interviews with 5 local-wisdom holders, and a group interview with 10 older adults. Phase 2 co-designed the program with 10 community participants, assessed content validity with 5 experts, and pilot-tested 6 core movements with 10 older adults. Phase 3 used a single-group pre–post design in 18 community-dwelling older adults aged 60 to 75 years. Participants completed an 8-week program, 3 sessions/week, 50 to 60 min/session. Outcomes included body composition, upper- and lower-body flexibility, 30-sec chair stand, 30-sec arm curl, a 6-min walk-derived cardiorespiratory score, agility, single-leg stance, and the Thai Active Aging Index (AAI). Paired *t* tests were supplemented with 95% confidence intervals, paired-effect sizes (*d_z*), and a Holm multiplicity sensitivity analysis. Phase 4 developed and disseminated a user manual and assessed stakeholder feedback and satisfaction. The results of participants and local-wisdom holders prioritized low-impact, adaptable, rhythmic, whole-body movements; cultural music; simple repetition; safety; and community ownership. The final program comprised 6 staff/sword-derived movements and had excellent expert content congruence (mean IOC = 0.97). All 10 pilot participants completed all 6 movements without modification. In the 18-person pre–post cohort, the results showed significant improvements in flexibility, lower-body strength, endurance, agility, and balance ($P < .05$); whereas, BMI, body fat, and upper-body strength did not significantly change ($P > .05$). The Active aging increased descriptively from 0.625 (moderate) to 0.925 (high); inferential statistics were unavailable. Manual satisfaction was high (overall mean = 4.53, SD = 0.57), and dissemination feedback emphasized enjoyment, social connection, cultural learning, and perceived health benefits. Therefore, the developed program was culturally acceptable, feasible, and associated with promising functional changes, particularly in cardiorespiratory endurance and balance. Because the effectiveness phase used a small single-group sample and multiple outcomes, the findings should be interpreted as preliminary. A fully powered randomized trial with documented adherence, adverse events, objective intensity monitoring, and validated active-ageing analysis is warranted.

Key Words: Active Ageing; Community-Based Participatory Research; Cultural Exercise; Functional Fitness; Older Adults; Thai Traditional Sports

INTRODUCTION

Population aging has made preservation of mobility, independence, and meaningful participation a central public-health priority. Thailand is aging rapidly, and national policy increasingly emphasizes not only longer life but also older adults' capacity to remain healthy, socially engaged, secure, and valued. The World Health Organization (WHO) conceptualizes active aging through opportunities for health, participation, and security, while more recent physical-activity guidance recommends that older adults combine aerobic activity with muscle-strengthening and multicomponent activities that emphasize functional balance. These principles shift the goal of exercise from isolated physiological gains toward continued participation in everyday and community life (20,21).

Aging is commonly accompanied by reductions in muscle strength and power, cardiorespiratory capacity, flexibility, postural control, and the ability to recover from perturbations. These changes can restrict daily activity and increase fall risk. Exercise can attenuate several of these trajectories. Resistance training improves muscle strength and functional capacity; whereas, programs that challenge balance and functional movement reduce falls among community-dwelling older adults (9,16). However, benefits depend on sustained participation. Programs that are unfamiliar, overly technical, expensive, or disconnected from local routines may be difficult to maintain, particularly after research supervision ends.

Culturally grounded movement offers a potentially useful bridge between exercise science and long-term participation. Dance and traditional movement combine repeated stepping, changes of direction, trunk rotation, upper-limb patterns, rhythm, memory, and social interaction. Reviews indicate that dance-based exercise can improve balance, strength, flexibility, mobility, and well-being in older adults (12,17). Thai studies likewise suggest that Thai dance, Thai boxing dance, and folk-performance exercise can improve physical function and balance (2,11,18). The cultural content may also support enjoyment, identity, and group belonging, which are factors that can increase participation beyond what is achieved by a technically sound but culturally neutral program.

The active-aging relevance of culturally grounded exercise is especially strong in northeastern Thailand. Older Thai adults describe health as the capacity to continue daily life, participation in maintaining social networks and meaningful community roles, and security in living with dignity and manageable dependence (19). Accordingly, older adults should not be treated only as recipients of an exercise prescription. Their experience can guide the selection of meaningful movements, acceptable music, safe progressions, and realistic delivery arrangements. Community-based participatory approaches formalize this role by involving community members in identifying needs, co-designing activities, interpreting feasibility, and planning dissemination (3).

Despite growing evidence for dance and traditional exercise, 3 gaps remain. First, many studies evaluate a pre-specified intervention without describing how older adults and local-wisdom holders shaped its content. Second, traditional activities are not always translated into a reproducible exercise prescription specifying frequency, intensity, time, type, volume, and progression. Third, most evaluations emphasize physical outcomes and give less attention to active aging, cultural transmission, and community implementation. The present study addressed these gaps by co-developing a Thai traditional sports exercise program based on

staff and sword movements, integrating local knowledge with exercise-science principles, pilot-testing its feasibility, evaluating preliminary pre–post changes in functional fitness and active aging, and developing a community-facing manual.

The primary purpose of this study was to develop a community-based participatory Thai traditional sports exercise program for older adults. Secondary aims were to: (a) examine expert content validity and movement feasibility; (b) estimate preliminary changes in health-related physical fitness and active aging after 8 weeks; and (c) describe dissemination feedback and manual satisfaction. We expected the program to be feasible and acceptable and to produce the clearest changes in outcomes directly trained by repeated stepping, weight transfer, trunk rotation, and single-leg control, namely lower-body functional strength, cardiorespiratory endurance, flexibility, agility, and balance.

METHODS

Study Design and Setting

This was a sequential, 4-phase participatory mixed-methods study combining qualitative formative work, co-design and feasibility testing, a single-group pre–post pilot, and community dissemination. The study was conducted in community settings in Mueang Udon Thani District, Udon Thani Province, northeastern Thailand. The main formative and effectiveness activities were centered in Nong Na Kham Subdistrict; the source report also identifies Ban Non Kok as a community knowledge site. Feasibility testing was conducted in Ban Sam Phrao, a nearby community with a similar context. The design is summarized in Table 1.

Table 1. Study Phases, Participants, Procedures, and Analytic Outputs.

Phase	Participants	Purpose	Core Procedures	Outputs/Analysis
1	5 local-wisdom holders; 10 older adults	Formative exploration	Document review; in-depth interviews; group interview; movement and cultural-context mapping	Content analysis; triangulation; member checking
2	10 co-design participants; 5 experts; 10 pilot participants	Program development and feasibility	Workshop co-design; FITT-VP specification; expert review; three-session movement pilot	IOC; feasibility observations; participant feedback
3	18 older adults, 60-75 years	Preliminary effectiveness	8 weeks; 3 sessions/week; 50-60 min/session; pre/post fitness and AAI assessment	Mean, SD, paired <i>t</i> test, 95% CI
4	5 older-adult demonstrators; dissemination stakeholders	Manual development and dissemination	Co-produce manual; train older coaches; community demonstration; feedback and satisfaction	Content analysis; mean and SD

Note. The participant groups served different functions across phases and should not be summed as a single analytic sample. The denominator for the Phase 4 satisfaction survey was not explicit in the source report and requires confirmation.

Phase 1: Formative Exploration

Participants and Recruitment

Local leaders nominated individuals with relevant knowledge or experience. Purposive sampling was used to recruit 5 local-wisdom holders with long-term involvement in Thai traditional sports and 10 older adults with experience in community exercise. Eligible participants were aged at least 60 years or held a relevant community role, could communicate in Thai, could describe their experience, and volunteered to participate. Individuals unable to communicate clearly or participate because of severe health limitations were excluded.

Data Collection

The research team developed semi-structured guides from literature on older-adult exercise, Thai traditional sports, community culture, and participatory program design. Interviews addressed: (a) traditional activities practiced locally; (b) movement characteristics; (c) perceived physical, psychological, and social value; (d) safety and modification needs; (e) suitable music and pacing; and (f) community roles in sustaining the activity. Individual interviews lasted approximately 10 to 20 min. The group interview lasted approximately 60 min. Sessions were audio-recorded with permission and supplemented by field notes describing movement demonstrations and contextual observations.

Qualitative Analysis and Trustworthiness

Recordings were transcribed, read repeatedly, and coded. Similar codes were grouped into categories aligned with the research aims while allowing context-specific concepts to emerge. The team compared information across document review, individual interviews, the group interview, and field observations. Credibility procedures reported in the source included triangulation, member checking, and expert review. Because the source report provided synthesized findings rather than verbatim transcripts, the present manuscript reports categories and themes without participant quotations.

Phase 2: Participatory Program Development and Feasibility

Co-Design Process

Ten older adults and community activity leaders participated in a workshop with the researchers and research assistants. Phase 1 findings were translated into design requirements: movements should be low impact, adaptable, slow-to-moderate and continuous, easy to remember, repeatable, and capable of engaging the arms, legs, and trunk. Participants preferred culturally recognizable staff and sword movements and local instrumental music. Researchers then mapped the selected movements to exercise-science principles and organized them using the FITT-VP framework.

Movement Selection and Biomechanical Rationale

Six core movements were retained: Tor Dam (grip/handle connection), Baek (carry), Thad Hu (ear-level guard), Hong Pik Hak/Yak (broken-wing or giant posture), Kakabat (cross), and Thep Ramphueng (contemplative deity posture). Across a cycle, the movements involved a ready position, step-and-strike pattern, single-leg knee lift, approximately 90° turning, cross-body strike, controlled deceleration, and reset. The intended motor demands included repeated sit-to-stand-like knee and hip extension, multidirectional stepping, trunk rotation, upper-limb control, dynamic weight transfer, and brief single-leg support. These elements provided a plausible training stimulus for lower-body function, balance, coordination, flexibility, and

cardiorespiratory endurance while preserving the aesthetic and cultural identity of the source activity.

Table 2. Final Exercise Prescription and Delivery Characteristics.

Component	Final Specification	Operational Detail
Frequency	3 sessions/week	Nonconsecutive community group sessions where feasible
Intensity	Music tempo 80-90 beats/min	Low-to-moderate movement intent; the protocol also listed 70-80% of age-predicted HRmax, but session-level HR data were not reported
Time	50-60 min/session	Warm-up, core traditional-sports sequence, and cool-down
Type	Thai staff/sword-derived whole-body exercise	Six core movements using controlled steps, turns, arm patterns, and balance tasks
Volume	Stretching 15 s/side × 2; core movements 8 cycles/movement × 2-3 rounds; cool-down stretching 15 s/side × 2	Volume was adapted to participant tolerance
Progression	Gradual overload	Increase from 2 to 3 rounds and improve movement continuity/control before increasing pace
Equipment	Lightweight staff/sword substitute and music	Community-deliverable, low-cost format
Supervision	Research team/community activity leader	Demonstration, cueing, fatigue observation, and movement modification

Note. BPM refers to musical tempo and should not be interpreted as heart rate. The discrepancy between tempo-based intensity and the stated 70-80% HRmax target requires author clarification before submission.

Expert Review and Pilot Testing

Five experts rated the congruence of program elements with the intended construct using an index of item-objective congruence (IOC; -1 = incongruent, 0 = uncertain, +1 = congruent). Item IOC values ranged from 0.80 to 1.00, and the mean IOC was 0.97. The program was then pilot-tested with ten older adults in Ban Sam Phrao across three 60-min sessions. The research team observed execution, continuity, fatigue, safety, enjoyment, and participation. All participants were able to perform all six core movements, and the source report stated that no movement required modification.

Phase 3: Preliminary Pre-Post Evaluation

Participants

Community-dwelling older adults aged 60-75 years were recruited from Nong Na Kham Subdistrict. The detailed inclusion criteria in the source report specified women, although the overview described both sexes; the analytic sample comprised 18 participants and sex was confirmed from the raw screening log. Eligibility required voluntary participation, the ability to complete community exercise, absence of a health condition that substantially limited movement, and a negative Physical Activity Readiness Questionnaire (PAR-Q). Exclusion criteria were missing more than 20% of sessions, an intervening illness or injury preventing continued participation, or voluntary withdrawal.

The source report stated that G*Power 3.1 yielded a minimum sample of 16 based on an effect size of 0.50 and 80% power, increased by 10% to 18. This calculation is retained as reported but requires rechecking because a conventional two-sided paired t test with $d_z = 0.50$, $\alpha = .05$, and 80% power requires approximately 34 complete participants. The study is therefore framed as a preliminary pilot rather than a definitive effectiveness trial [8].

Intervention

Participants completed the finalized program for 8 weeks, 3 days per week, for 50-60 min per session. Each session included a warm-up, the six-movement traditional-sports sequence, and a cool-down. Movement cadence was supported by 80-90 beats/min music. The protocol indicated progression by adding rounds and increasing continuity while maintaining technique. The source report did not provide individual attendance, achieved heart rate, rating of perceived exertion, adverse-event counts, or protocol-deviation data; these should be recovered from field records if available.

Outcome Measures

Body Composition. Body mass index (BMI, kg/m^2) and percentage body fat were assessed before and after the intervention. The source report did not identify the body-composition device or equation (AccunIQ BC300, Germany).

Flexibility. Upper-body flexibility was assessed using right and left back-scratch tests (cm), where values closer to zero or positive indicate better reach. Trunk/hamstring flexibility was assessed using a sit-and-reach test (cm) (1).

Functional Muscular Endurance. Lower-body function was assessed with the 30-s chair-stand test (repetitions), and upper-body endurance with the 30-s arm-curl test (repetitions) (1).

Cardiorespiratory Endurance. A 6-min walk procedure was used. The source outcome table reported a derived value in $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ rather than the standard 6-min walking distance in meters; the conversion equation and unit must be verified. The manuscript therefore refers to this variable as the 6-min walk-derived cardiorespiratory score (1).

Agility and Balance. A timed agility course (s; lower is better) and single-leg stance (s; higher is better) were used. The source cites the Thai Department of Physical Education and the Senior Fitness Test framework (1).

Active Aging. The Thai AAI combined 4 equally weighted domains: health (6 indicators), participation (4), security (4), and enabling environment (2). Scores range from 0 to 1 and were categorized as low (0.000-0.499), moderate (0.500-0.799), or high (0.800-1.000) (22).

Statistical Analysis

The data are presented as mean and standard deviation. Differences between pre- and post-intervention measurements were analyzed using a paired t -test. Statistical significance was set at $P < .05$. Data were analyzed using IBM SPSS Statistics for Windows, version 21.0 (IBM Corp., Armonk, NY, USA).

Phase 4: Manual Development and Dissemination

Five older adults who had completed Phase 3 and could demonstrate the movements participated in manual development and coach preparation. The manual included movement sequence, photographs, instructions, music/cadence guidance, session structure, and safety precautions. Dissemination included community readiness meetings, formation of an older-adult coaching team, demonstrations for community members and younger people, and coordination with local organizations. Feedback was collected through observation and group

discussion. Satisfaction was assessed with a 12-item, 5-point Likert questionnaire and summarized using mean and SD. The questionnaire denominator was not clearly stated in the source report.

Ethical Considerations: This study was approved by the Research Ethics Review Committee of Udon Thani Rajabhat University on September 29, 2025 (approval no. 0622.7/655). All participants received written information regarding the study's purpose, procedures, confidentiality, and right to withdraw. Written informed consent was obtained from each participant before data collection.

RESULTS

Phase 1: Formative Findings

Local-wisdom holders reported 20 to 50 years of involvement as practitioners and transmitters of traditional sports. Document review and participant accounts converged on 4 program-development themes. First, traditional staff, sword, Krabi-Krabong, Muay Thai, and Wai Kru movements could provide continuous whole-body activity involving stepping, striking patterns, turning, arm elevation, trunk rotation, balance, and coordination. Second, suitability for older adults depended on reducing impact and speed, simplifying sequences, allowing support or reduced range of motion, and avoiding uncontrolled weapon momentum. Third, familiar music and repeated group movement were viewed as sources of enjoyment, stress reduction, learning, and motivation. Fourth, an acceptable program should preserve cultural meaning and create roles for older adults as teachers and community leaders rather than positioning them only as exercise recipients.

The participants specifically requested movements that were not forceful or jarring, could be adapted for knee pain or limited balance, progressed slowly, used the whole body, and were repeated enough to be remembered. These requirements shaped the safety cues, the selection of 6 core postures, and the group-delivery format. Also, the findings identified an implementation gap: traditional movements were practiced locally, but communities lacked a standardized, measurable, older-adult-specific program and manual.

Phase 2: Program Validity and Feasibility

The participatory workshop produced the FITT-VP program described in Table 2. Expert ratings supported excellent content congruence (mean IOC = 0.97; item range 0.80-1.00). Lower item IOC values of 0.80 occurred for ease of performance, selected postures, music-movement fit, and the 80-90 beats/min tempo, but all values remained above the study's acceptance threshold. During the 3-session pilot, all 10 older adults performed all 6 core movements. Observations indicated that slow instruction, emphasizing technique before continuity, and maintaining a consistent rhythm supported safe group performance. No movement was formally removed or modified after pilot testing; adverse-event reporting was not included in the source report.

Phase 3: Participant Characteristics

The characteristics of the 18 participants before and after the intervention. Overall, body mass, BMI, resting heart rate, and blood pressure remained relatively stable; whereas, mean age

increased slightly because post-intervention assessments were conducted during the subsequent reporting period. In Table 3.

Table 3. Characteristics of the Experimental Group.

Characteristic	Pre-Intervention	Post-Intervention
Age (years)	65.50 ± 5.55	65.67 ± 5.57
Body mass (kg)	58.01 ± 8.05	57.84 ± 8.05
BMI (kg/m ²)	25.13 ± 3.43	25.01 ± 3.40
Resting heart rate (beats/min)	84.22 ± 17.04	76.22 ± 8.45
Systolic blood pressure (mmHg)	142.33 ± 15.42	141.72 ± 21.04
Diastolic blood pressure (mmHg)	81.39 ± 9.68	77.44 ± 12.04

Note. Values are mean ± SD. The slight change in mean age reflects the timing of post-testing as reported in the source. Sex distribution, comorbidity profile, medication use, and attendance should be added from participant records.

The results showed significant improvements in back-scratch flexibility on both the right (mean change = 3.53 cm, $P = .047$) and left sides (mean change = 4.83 cm, $P = .009$), sit-and-reach flexibility (mean change = 3.64 cm, $P = .035$), the 30-second chair-stand test (mean change = 2.11 repetitions, $P = .027$), the 6-minute walk distance (mean change = 2.19 laps, $P < .001$), agility performance (mean change = -3.30 seconds, $P = .031$), and single-leg stance time (mean change = 9.13 seconds, $P = .004$). In contrast, no significant changes were observed in BMI, body fat percentage, or the 30-second arm-curl test ($P > .05$). In Table 4

Table 4. Pre–Post Fitness Outcomes, Confidence Intervals, Multiplicity Sensitivity, and Paired Effect Sizes.

Outcome	Pre	Post	Change [95% CI]	t	p
BMI (kg/m ²)	25.13 ± 3.44	25.01 ± 3.40	-0.12 [-0.94, +0.70]	0.309	.761
Body fat (%)	32.88 ± 4.17	32.95 ± 4.09	+0.07 [-1.15, +1.29]	-0.121	.905
Back scratch, right (cm)	-8.50 ± 11.29	-4.97 ± 6.29	+3.53 [+0.06, +7.00]	-2.146	.047
Back scratch, left (cm)	-10.72 ± 7.80	-5.89 ± 6.69	+4.83 [+1.35, +8.31]	-2.930	.009
Sit-and-reach (cm)	8.12 ± 6.94	11.76 ± 4.53	+3.64 [+0.29, +6.99]	-2.295	.035
30-s chair stand (reps)	13.67 ± 3.61	15.78 ± 3.30	+2.11 [+0.27, +3.95]	-2.426	.027
30-s arm curl (reps)	21.61 ± 4.94	22.78 ± 5.02	+1.17 [-0.49, +2.83]	-1.486	.155
6-min walk-derived score*	32.14 ± 3.86	34.33 ± 2.10	+2.19 [+1.34, +3.04]	5.468	<.001
Agility course (s)	17.21 ± 3.08	13.91 ± 1.99	-3.30 [-6.26, -0.34]	-2.350	.031
Single-leg stance (s)	11.86 ± 7.48	20.99 ± 9.47	+9.13 [+3.33, +14.93]	-3.320	.004

Note. n = 18. Change = post minus pre. For agility time, a negative change indicates improvement.

*The source reported the 6-min walk-derived outcome in mL·kg⁻¹·min⁻¹; the scoring equation and unit require verification.

Active Aging

The mean AAI increased descriptively from 0.625, categorized as moderate to 0.925 categorized as high. The source table listed SDs of 1.52 and 1.71, which are incompatible with a scale bounded between 0 and 1 and were therefore not reproduced. No paired test, confidence interval, or domain-level results were reported. Consequently, the AAI finding should be treated as descriptive until the scoring spreadsheet and participant-level values are verified.

Phase 4: Dissemination and Manual Acceptability

Dissemination feedback was positive across older-adult coaches, participating older adults, younger community members, and local organizations. Older coaches reported increased confidence, pride in transmitting local knowledge, and improved ability to lead and adapt activities. Older participants emphasized enjoyment, reduced stress, greater interaction with peers, perceived improvements in sleep and musculoskeletal comfort, and increased motivation to exercise. Younger participants described cultural learning and stronger intergenerational relationships. Local organizations provided space, equipment, and publicity and expressed interest in integrating the program into health-promotion activities. These findings were based on observations and summarized group feedback rather than a formally coded quotation set.

Table 5. Satisfaction with the Thai Traditional Sports Exercise Manual.

Item	Evaluation Statement	Mean	SD
1	Content was clear and understandable.	4.62	0.51
2	Content sequence was appropriate.	4.55	0.58
3	Language was appropriate and easy to understand.	4.60	0.54
4	Illustrations were clear and understandable.	4.48	0.63
5	Content was accurate and credible.	4.66	0.49
6	The manual could be applied in practice.	4.52	0.57
7	Exercise intensity was appropriate.	4.40	0.65
8	Exercise duration was appropriate.	4.38	0.68
9	The manual increased exercise knowledge.	4.58	0.52
10	The manual increased exercise motivation.	4.45	0.60
11	The manual was convenient to use.	4.50	0.56
12	Overall satisfaction.	4.57	0.53
—	Overall across items	4.53	0.57

Note. Five-point response scale. The source report's interpretation classified 4.51-5.00 as the highest satisfaction level and 3.51-4.50 as high. The number of questionnaire respondents must be confirmed.

DISCUSSION

Principal Findings

This study developed a reproducible Thai traditional sports exercise program through a sequence that began with local knowledge that was translated into an exercise-science prescription, tested movement feasibility, estimated preliminary functional outcomes, and returned the program to the community through a manual and older-adult coaches. Three findings are most important. First, participatory co-design produced a program that was both culturally recognizable and operationally specific. Second, the 8-week pilot showed promising changes in several directly trained outcomes, with the strongest multiplicity-robust findings for the 6-min walk-derived cardiorespiratory score and single-leg stance. Third, dissemination findings suggest that cultural meaning, music, group participation, and leadership roles may contribute to acceptability beyond the physical stimulus alone.

Why Cardiorespiratory Endurance and Balance May Have Improved

The program required continuous whole-body movement for 50 to 60 min, 3 times per week, using repeated stepping, arm movement, trunk rotation, and transitions among postures. This structure could increase cumulative aerobic demand even when individual movements are low impact. The large paired effect for the 6-min walk-derived score is consistent with Thai dance research showing improved walking capacity after 6 weeks of thrice-weekly practice and with broader evidence that dance can improve endurance and mobility (11,17). Nevertheless, the present outcome's scoring equation and unit must be verified; until then, the physiological magnitude should be interpreted cautiously.

The increase in single-leg stance is biomechanically plausible. The sequence repeatedly narrowed the base of support during knee lifts, shifted the center of mass during steps and turns, and required controlled deceleration and realignment. These tasks stimulate anticipatory postural adjustments, ankle and hip strategies, proprioceptive processing, and coordination between the trunk and lower limbs. The result aligns with randomized evidence that a Thai boxing dance program improved balance among older adults at fall risk (2) and with reviews showing that balance- and function-focused exercise reduces falls in community-dwelling older people (16). The present study measured performance rather than falls, however, and should not claim fall prevention without prospective fall surveillance.

Flexibility, Lower-Body Function, and Specificity

Unadjusted improvements in both back-scratch directions, sit-and-reach, and chair-stand performance were moderate in magnitude. Repeated reaching and staff handling may have increased exposure to shoulder and trunk ranges of motion, while warm-up and cool-down stretching added a direct flexibility stimulus. Repeated knee and hip flexion-extension, stepping, and controlled lowering provide body-mass resistance resembling functional sit-to-stand training. These features are consistent with evidence that progressive resistance and multicomponent exercise improve functional capacity in older adults (9). Because the program did not quantify range of motion, external load, or repetition velocity, the mechanisms remain inferential.

The absence of a significant arm-curl change reinforces the principle of training specificity. Although the movements used the arms, the staff/sword substitute appears to have provided limited external resistance. Motor control and endurance demands do not necessarily reach the loading threshold required to increase arm-curl repetitions. A future version could add a carefully progressed upper-body resistance component without compromising the cultural form. Similarly, unchanged BMI and body fat are unsurprising over 8 weeks without dietary control and with an intervention primarily designed for function rather than energy deficit. Body-composition change should not be treated as a necessary marker of program success in this context.

Active Aging and Community Participation

The descriptive rise in AAI is conceptually compatible with the intervention but cannot yet be treated as a validated treatment effect. The program may influence the health domain through exercise and perceived function, the participation domain through group activity and teaching roles, and the enabling environment through community organization. However, security indicators such as income and housing are unlikely to change substantially during an eight-week exercise program. A jump from 0.625 to 0.925 is therefore unexpectedly large and should

prompt item-level scoring verification. Domain-level analysis would clarify whether the increase was driven by modifiable health and participation items or by coding changes unrelated to the intervention.

The qualitative findings nevertheless show why active aging is a useful framework. Older adults valued being able to teach, preserve local knowledge, interact with younger people, and contribute visibly to community life. These priorities mirror qualitative research in northeastern Thailand, where active aging is understood through continued daily function, meaningful participation, social respect, and security in relation to family and community (19). The participatory approach therefore adds more than acceptability; it aligns the intervention with locally meaningful definitions of ageing well.

Acceptability, Cultural Relevance, and Sustainability

Manual satisfaction and dissemination feedback indicate strong perceived usability. The highest-rated attributes were credibility, clarity, and accessible language. The comparatively lower, but still high ratings for intensity and duration are informative: participants may value the program while still needing flexible pacing and session-length options. Future implementation should offer a shorter entry-level version, seated or supported modifications, and clear progression criteria. It should also specify the competence required of community coaches and the process for managing pain, dizziness, elevated blood pressure, or loss of balance.

Enjoyment, familiar music, and group identity may be important adherence mechanisms. In a 12-month community dance program, participants identified music, adaptability, instruction quality, and the group environment as facilitators, and adherence remained above 70% [4]. The present study did not report attendance quantitatively, but the same mechanisms were evident in participant feedback. Training older adults as coaches may further strengthen ownership and intergenerational cultural transmission, although fidelity and safety monitoring are necessary when delivery expands beyond the research team.

CONCLUSIONS

A community-based participatory process successfully transformed Thai traditional staff and sword movements into a structured, expert-reviewed, and feasible exercise program for older adults. Eight weeks of group practice was associated with promising improvements in cardiorespiratory performance and balance, with additional unadjusted gains in flexibility, agility, and lower-body functional endurance. The program and manual were well received and created meaningful roles for older adults as cultural and exercise leaders.

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Combined Corrective Exercise and Foam Surface Balance Training in Older Adults with Forward Head Posture: A Randomized Controlled Trial on Pain, Cervical Disability, and Postural Balance

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ABSTRACT

Nakarin W, Pimonpan T, Pornpimol M. Combined Corrective Exercise and Foam Surface Balance Training in Older Adults with Forward Head Posture: A Randomized Controlled Trial on Pain, Cervical Disability, and Postural Balance. The purpose of this study was to compare the effects of posture education, corrective exercise on a stable surface, and corrective exercise on a foam surface on craniovertebral angle (CVA), pressure pain threshold (PPT), muscle strength, pelvic tilt angle, neck disability, and functional mobility in older adults with forward head posture (FHP). Sixty-nine community dwelling older adults (60 to 80 years of age) with FHP (CVA < 50°) were randomized to Control Education Group (CON), Corrective Exercise on a Hard Surface (CE+HARD), or Corrective Exercise on a Foam Surface (CE+FOAM). Exercise Groups completed a home-based, 3 times per week protocol for 6 weeks targeting the cervical and scapular postural muscles. Outcomes were assessed at baseline and week 6. All Groups showed a comparable increase in CVA over time (main effect of time, $P < 0.001$), with no significant group $\times$ time interaction. Both corrective exercise Groups showed significant improvements relative to the CON Group in PPT, muscle strength, pelvic tilt angle, and Neck Disability Index (all $P < 0.05$), with no consistent advantage of the foam surface training over the hard surface training. Also, timed Up and Go performance did not change significantly in any Group. Six weeks of home-based corrective exercise improved pain sensitivity, muscle strength, pelvic alignment, and neck-related disability in older adults with FHP, independent of measurable change in CVA or functional mobility. Foam surface training conferred no consistent additional benefit over hard surface training.

Key Words: Corrective Exercise, Forward Head Posture, Older Adults, Postural Control

INTRODUCTION

Aging is associated with progressive musculoskeletal decline, including reduced muscle strength, joint flexibility, proprioception, and postural stability (6,7). Among postural disorders common in older adults, forward head posture (FHP) characterized by anterior displacement of the head and altered cervical alignment increases mechanical loading on cervical structures, (3) and it is associated with neck pain, headache, temporomandibular dysfunction, and muscular imbalance, including tightness of the suboccipital and pectoral muscles alongside weakness of the deep cervical flexors, scapular stabilizers, and thoracic extensors (10). In older adults, FHP may further contribute to thoracic kyphosis, anterior shift of the center of gravity, impaired postural control, and elevated fall risk (7), thereby compromising functional mobility and quality of life.

The physical consequences of FHP are not isolated but form an interconnected chain of impairment. Sustained anterior head translation increases cumulative mechanical load on cervical and upper thoracic structures, generating pain as the primary nociceptive signal of tissue stress (10). Persistent pain and structural malalignment together restrict cervical range of motion and functional capacity, which is captured clinically by the Neck Disability Index (NDI) as a composite measure of pain-related activity limitation (16). Underlying both pain and disability is a pattern of muscular imbalance (i.e., lengthened, weakened deep cervical flexors and scapular stabilizers opposing shortened suboccipital and pectoral muscles) that is quantified through manual muscle testing (MMT) and represents the neuromuscular substrate on which corrective exercise acts directly (20).

Because the cervical spine and cranio-vertebral region contribute proprioceptive input to postural control, this muscular imbalance and the compensatory thoracic kyphosis it produces also displace the body's center of gravity anteriorly, degrading balance and increasing fall risk in older adults (7). This postural chain does not terminate at the trunk. The compensatory adjustments at the thoracic spine are frequently transmitted caudally to the lumbo-pelvic region, altering pelvic angle (commonly anterior pelvic tilt) as the spine and pelvis realign to maintain overall postural equilibrium (2,5). Taken together, pain, NDI, MMT, balance, and pelvic angle represent sequential and interdependent markers along a single postural-dysfunction continuum, thus justifying their combined assessment when evaluating any corrective intervention in this population.

Corrective exercises that combine stretching of the shortened muscles with strengthening of the weakened postural stabilizers has been shown to reduce pain, improve cervical alignment, and enhance functional capacity in individuals with postural dysfunction (9,12,13). Separately, balance training on unstable surfaces (e.g., foam pads) imposes proprioceptive demands that improve postural control and functional mobility while lowering fall risk in older adults (11,22). Yet, despite evidence supporting each intervention independently, no study has examined the combined effect across the full chain of outcomes of pain, NDI, MMT, balance, and pelvic angle in older adults with FHP, particularly within the Thai population.

Prior research has typically assessed isolated outcomes (e.g., pain and NDI alone, or balance alone), leaving unclear whether a combined corrective exercise and balance training program can simultaneously address impairment at each level of this postural-dysfunction chain.

Therefore, the purpose of this study was to investigate the effects of a combined corrective exercise and foam surface balance training program on pain, cervical disability, muscle strength, balance, and pelvic alignment in Thai older adults with FHP, providing evidence to inform exercise-based strategies for improving physical function, reducing fall risk, and enhancing quality of life in this population.

METHODS

Subjects

Community-dwelling older adults aged 60 to 80 years were recruited from Saensuk Subdistrict and the surrounding areas, Chonburi Province, Thailand. The **Inclusion Criteria** were: (a) craniovertebral angle (CVA) of less than 50°, indicating forward head posture (3); and (b) the ability to walk independently for at least 3 meters without lower-extremity pain. The **Exclusion Criteria** included: (a) a history of spinal surgery; (b) acute injury or acute symptomatology of the neck, back, or spine; (c) uncorrected visual impairment; (d) neurological or vestibular disorders affecting posture and/or gait (such as stroke, Ménière's disease, and vertigo); (e) musculoskeletal conditions of the lower limbs affecting independent standing or walking (e.g., rheumatoid arthritis, severe osteoarthritis, or other soft-tissue disorders); and (f) chronic illness or medication use associated with increased fall risk (e.g., antihistamines, anti-vertigo agents, or drugs causing drowsiness or postural hypotension).

All the participants were informed of the study procedures, risks, and benefits, and they provided written informed consent prior to enrollment. The study protocol was approved by the Institutional Ethics Committee (IRB3-101/2567), and it was conducted in accordance with the 2013 revision of the Declaration of Helsinki.

The sample size was calculated using G*Power software (fixed-effects, one-way ANOVA, omnibus F-test), with an effect size of 0.55, $\alpha = 0.05$, and power $(1-\beta) = 0.95$, yielding a minimum requirement of 57 participants. Accounting for an anticipated 20% attrition rate ($n = 12$), the target sample size was increased to 69 participants who were allocated equally across 3 Groups ($n = 23$ per Group). Sample size estimation was based on CVA as the primary outcome; consequently, this study may have been underpowered to detect between-group differences in secondary outcomes.

Procedures

Study Design

This study was a randomized controlled trial with participant and outcome-assessor blinding. Blinding of exercise supervisors was not feasible given the nature of the intervention; to mitigate potential performance bias, supervisors received standardized training in intervention delivery and had no involvement in outcome assessment. The participants were randomly allocated to 1 of 3 Groups: (a) the Control Education (CON); (b) the Corrective Exercise on a Hard Surface Group (CE+HARD); or (c) the Corrective Exercise on a Foam Surface Group (CE+FOAM), using a sealed opaque-container ("black box") method in which each participant drew one allocation slip without prior knowledge of Group assignment, which ensured concealment from both the participants and the investigators.

The intervention period spanned 6 weeks, during which the participants completed home-based exercise sessions 3 times per week according to a structured protocol. Adherence was

monitored via standardized exercise logs, in which the participants recorded session date, duration, and any difficulties encountered. The outcome measures were assessed at baseline and at post-intervention (week 6).

Interventions

Control (CON)

The participants: (a) received postural education from licensed physical therapists, including a printed illustrated manual on ergonomic posture (e.g., proper sitting alignment); and (b) were instructed to continue their usual daily activities without initiating structured exercise.

Corrective Exercise on Hard Surface (CE+HARD)

The participants completed a 6-week, home-based corrective exercise program performed on a firm floor surface, adapted from our previous randomized controlled trial (22) and designed to improve postural alignment through combined strengthening and flexibility training. Sessions were performed 3 times weekly for approximately 20 to 30 minutes and targeted the lower trapezius, middle trapezius, serratus anterior, pectoralis muscles, and cervical extensors. The protocol comprised postural strengthening and stretching/flexibility exercises that required no additional equipment. Full protocol details and exercise positions are presented in Table 1 of our previous study (22).

Corrective Exercise on Foam Surface (CE+FOAM)

The participants followed the identical 6-week exercise protocol that the CE+HARD Group had performed, with all the exercises performed on a foam pad (approximately 0.25 to 0.45 m width × 0.20 to 0.30 m length × 0.03 to 0.10 m thickness). Comparable foam surfaces have been used previously to impose proprioceptive and balance challenges in older adults (11,14). All the exercises were performed in the standing position to maximize demands on balance and muscular control.

Outcome Measures

Craniovertebral Angle (CVA)

CVA, an index of forward head posture, was measured with markers placed at the C7 spinous process and tragus while the participant sat facing forward with the back supported. Lateral-view photographs were captured with the camera positioned 1 meter from the participant, which followed a standardized protocol from previous work (15,22). CVA was calculated as the angle formed between the horizontal line and the line connecting C7 and the tragus that was measured with a protractor. Three images were captured per assessment and averaged for analysis. This method has demonstrated high reliability (ICC = 0.91) (15).

Pelvic Tilt Angle

Pelvic tilt was assessed using an anthropometer fitted with a digital protractor inclinometer (Level Box Angle), positioned level and secured firmly over the sacrum. Higher values corresponded to greater anterior pelvic tilt, and lower values to reduced anterior tilt (17).

Pressure Pain Threshold (PPT)

PPT was assessed bilaterally at the upper trapezius, levator scapulae, and temporalis muscles using a digital pressure algometer (The Commander Algometer, JTECH Medical, Salt Lake City, UT, USA). Pressure was applied until the participants reported a transition from pressure

to pain, at which point the examiner terminated the trial. Two measurements were taken per site with a 30-second rest interval, and the mean of the 2 trials was used for statistical analysis (18).

Manual Muscle Test (MMT)

Muscle strength of the serratus anterior, lower trapezius, and sternocleidomastoid was assessed bilaterally using a digital handheld dynamometer (MicroFET3, Hoggan Industries Inc., West Jordan, UT, USA). The participants performed a 4-second isometric contraction against resistance, with force recorded in kilograms. Prior to formal testing, the participants completed 2 submaximal (70 to 80% effort) practice trials with a 1-minute rest to familiarize themselves with correct positioning and effort, followed by a single test trial per muscle group (1). Hand-held dynamometry has demonstrated acceptable reliability for muscle-strength assessment in older adults (1).

Thai Neck Disability Index (NDI-TH)

The NDI-TH comprises 10 domains: pain intensity, personal care, lifting, reading, headache, concentration, work, driving, sleeping, and recreation/leisure activity. Each domain is scored from 0 to 5, and the total score is converted to a percentage that reflected the degree to which neck pain limited daily function: 0 to 9% = no disability, 10 to 29% = mild disability, 30 to 49% = moderate disability, and $\geq 50\%$ = severe disability (16).

Timed Up and Go (TUG) Test

The TUG Test assessed functional mobility and fall risk. The participants began seated in a chair and upon the examiner's signal, stood, walked 3 meters, turned, returned to the chair, and sat down. The time to complete the task was recorded. The TUG demonstrates excellent test-retest reliability (ICC = 0.99) (21). Three trials were performed and analyzed.

Statistical Analyses

Normality of all variables was assessed using the Shapiro–Wilk Test. Normally distributed continuous data are presented as mean $\pm$ SD; whereas, NDI-TH is presented as median (IQR). Baseline between-group differences were compared using one-way ANOVA for normally distributed data and appropriate non-parametric tests for non-normally distributed data. Time, group, and time $\times$ group interaction effects for parametric outcomes were examined using mixed-model ANOVA [time (pre, post 6-week intervention) $\times$ group (CON, CE+HARD, CE+FOAM)]. Significant interactions were followed by *post hoc* comparisons with Bonferroni adjustment. Effect sizes were reported as partial eta-squared (η^2p) for mixed-ANOVA effects (small = 0.02, moderate = 0.13, large = 0.26) and Cohen's d for pairwise comparisons (small = 0.2, moderate = 0.5, large = 0.8). NDI-TH was analyzed non-parametrically because of its non-normal distribution. Statistical significance was set at $P < 0.05$. Analyses were performed using IBM SPSS Statistics, version 20.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Participant Characteristics

All 69 participants with FHP completed the 6-week, 3 times per week exercise program with no reported incidents of falls or exercise-related soreness. Baseline demographic and physical

characteristics did not differ significantly between the 3 Groups (Table 1), and no significant between-group difference was observed in FHP severity as measured by baseline CVA.

Table 1. Descriptive Data of the Participants.

	CON (n = 23)	CE+HARD (n = 23)	CE+FOAM (n = 23)	P-value
Age (yrs)	67.0 ± 4.2	67.2 ± 5.9	66.2 ± 3.2	0.752
Gender (W/M)	19/4	19/4	15/8	0.272
Weight (kg)	61.7 ± 11.3	59.2 ± 11.4	62.8 ± 14.8	0.925
Height (cm)	158.9 ± 7.8	158.2 ± 5.9	158.9 ± 8.1	0.618
BMI (kg/m ²)	24.5 ± 4.3	23.6 ± 3.8	25.0 ± 5.7	0.567
CVA (°)	39.7 ± 6.1	37.9 ± 5.9	40.9 ± 4.5	0.139

Data are mean ± SD data. **CVA**, Craniovertebral angle; **CON**, Control Group; **CE+HARD**, Corrective Exercise on Hard Surface; **CE+FOAM**, Corrective Exercise on Foam Surface.

Craniovertebral Angle

Changes in CVA following the 6-week intervention are presented in Figure 1. Mixed-model ANOVA revealed a significant main effect of time ($F(1,66) = 158.1$, $P < 0.001$, $\eta^2p = 0.71$) with all 3 Groups showing a comparable increase in CVA, which averaged 5.4° (95% CI: 4.6 – 6.3°). No significant time × group interaction or main effect of group was observed, indicating that the magnitude of CVA change did not differ across the 3 Groups.

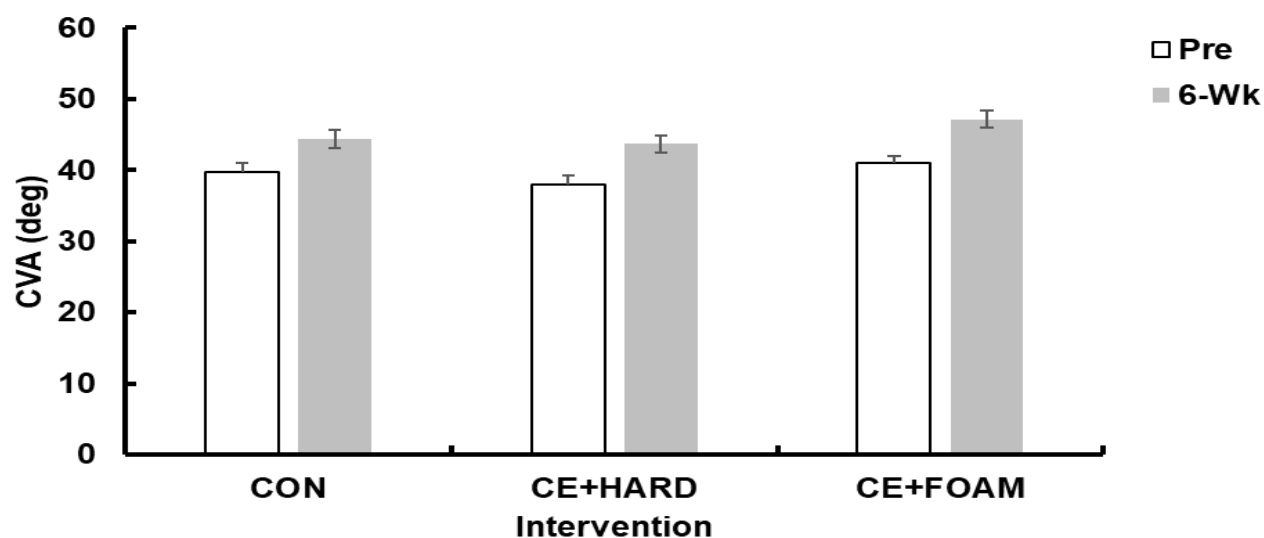


Figure 1. CVA Changes as a Result of Intervention. Data are mean and SEM (N = 23). CVA, craniovertebral angle; **CON**, Control Group; **CE+HARD**, Corrective Exercise on Hard Surface Group; **CE+FOAM**, Corrective Exercise on Foam Surface Group. No time × group interaction effect was seen in this measurement.

Secondary Outcomes

Results of the exploratory analyses for secondary outcomes are summarized in Table 2.

Pelvic Tilt Angle

A significant time × group interaction and main effect of time were observed for both right and left pelvic tilt angle. Pelvic tilt decreased significantly in both CE+HARD and CE+FOAM Groups

following the intervention (all $P < 0.001$) with no significant difference between the 2 “exercise” Groups; whereas, pelvic tilt remained unchanged in the CON Group.

Pressure Pain Threshold

A significant time $\times$ group interaction and main effect of time were observed for PPT across all assessed muscles. Both corrective “exercise” Groups showed increased PPT following the intervention (CE+HARD in all muscles except the right temporalis and CE+FOAM in all muscles bilaterally with no significant difference between the 2 exercise Groups). In contrast, PPT remained largely unchanged or decreased in the CON Group.

Manual Muscle Test

A significant time $\times$ group interaction and main effect of time were likewise observed for MMT across all muscles tested. Muscle strength increased post-intervention in both “exercise” Groups (CE+HARD across all muscles, and CE+FOAM in all muscles except the right sternocleidomastoid) with the CE+FOAM Group showing a significantly greater increase specifically in right lower trapezius strength relative to CE+HARD ($P = 0.046$). MMT values in the CON Group remained largely unchanged or decreased.

Balance

Balance outcomes following training are presented in Figure 2. No significant time $\times$ group interaction, main effect of time, or main effect of group was observed for this measure.

Neck Disability Index

Non-parametric analysis revealed a significant worsening in NDI score in the CON Group ($P = 0.047$); whereas, both “exercise” Groups showed significant improvement (CE+HARD: $P = 0.003$; CE+FOAM: $P < 0.001$) with no significant difference between the 2 “exercise” Groups (Table 2).

Table 2. Data for Pelvic Tilt Angle, Pain, Strength, Neck Disability Index (N = 23).

VARIABLES	CON		CE+HARD		CE+FOAM	
	PRE	6-Wk	PRE	6-Wk	PRE	6-Wk
PELVIC TILT ANGLE (°)						
RIGHT	12.0 $\pm$ 2.7	12.1 $\pm$ 2.7	12.1 $\pm$ 1.7	11.7 $\pm$ 1.7	12.4 $\pm$ 2.9	11.9 $\pm$ 2.8
INTERACTION EFFECT ($P < 0.001$); TIME EFFECT ($P < 0.001$); GROUP EFFECT ($P = 0.924$)						
LEFT	11.9 $\pm$ 2.7	12.1 $\pm$ 2.7	12.1 $\pm$ 1.7	11.7 $\pm$ 1.7	12.4 $\pm$ 2.9	11.9 $\pm$ 2.8
INTERACTION EFFECT ($P < 0.001$); TIME EFFECT ($P < 0.001$); GROUP EFFECT ($P = 0.908$)						
PPT (kg)						
RT. UPPER TRAPEZIUS	38.8 $\pm$ 10.0	38.6 $\pm$ 10.0	33.0 $\pm$ 8.9	33.8 $\pm$ 8.9	37.2 $\pm$ 11.9	38.5 $\pm$ 11.9

VARIABLES	CON		CE+HARD		CE+FOAM	
	PRE	6-Wk	PRE	6-Wk	PRE	6-Wk
LT. LOWER TRAPEZIUS	9.8 ± 2.5	9.6 ± 2.4	7.5 ± 2.3	8.2 ± 2.4	8.9 ± 1.6	9.7 ± 1.8
INTERACTION EFFECT (P < 0.001); TIME EFFECT (P < 0.001); GROUP EFFECT (P = 0.015)						
Rt. STERNOCLEIDOMASTOID	7.1 ± 2.5	7.3 ± 2.3	6.4 ± 1.5	7.0 ± 1.4	7.1 ± 1.1	7.3 ± 1.0
INTERACTION EFFECT (P < 0.001); TIME EFFECT (P < 0.001); GROUP EFFECT (P = 0.560)						
Lt. STERNOCLEIDOMASTOID	7.3 ± 2.3	6.9 ± 2.2	6.5 ± 1.6	6.9 ± 1.4	7.0 ± 1.1	7.2 ± 1.0
INTERACTION EFFECT (P < 0.001); TIME EFFECT (P = 0.019); GROUP EFFECT (P = 0.613)						
NECK DISABILITY INDEX (SCORES)						
NDI-TH	0 (2)	2 (3)	2 (10)	1 (5)	12 (18)	5 (9)
BETWEEN-GROUP MEDIAN TEST: PRE (P = 0.002); 6-WK (P = 0.461)						

Values are mean ± SD except NDI-TH, which is presented as median (IQR). Abbreviations: **CON**, Control Group; **CE+HARD**, Corrective Exercise on Hard Surface; **CE+FOAM**, Corrective Exercise on Foam Surface; **PPT**, Pressure Pain Threshold; **NDI-TH**, Thai Version of the Neck Disability Index.

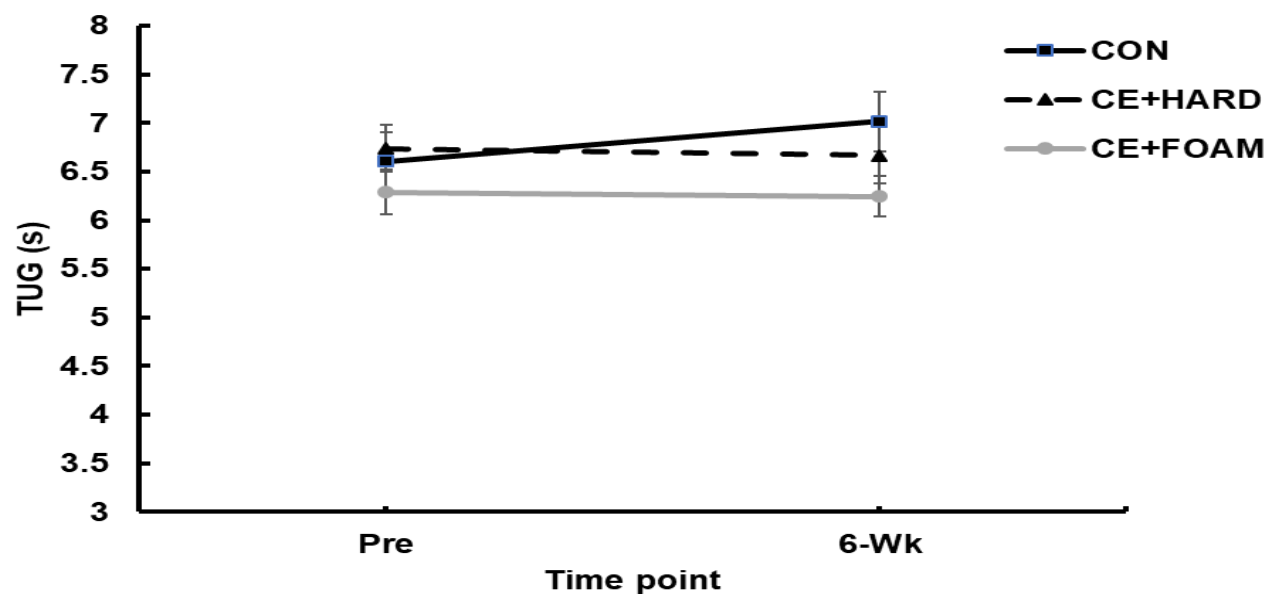


Figure 2. Changes in TUG as a Result of Intervention. Data are mean and SEM (N = 23). TUG, Timed Up and Go; **CON**, Control Group; **CE+HARD**, Corrective Exercise on Hard Surface; **CE+FOAM**, Corrective Exercise on Foam Surface. No time × group interaction effect was seen in this measurement.

DISCUSSION

The present study compared postural education with corrective exercise performed on stable and foam surfaces in older adults with FHP. The principal findings were significant group × time interactions for most secondary outcomes with the notable exceptions of CVA and the TUG Test.

Contrary to our primary hypothesis, the absence of a significant group × time interaction for CVA indicates that the pattern of postural change did not differ significantly among the 3 Groups, despite all Groups showing a modest increase in angle over time. This finding contrasts with previous research reporting that corrective exercise involving stretching of shortened muscles and strengthening of weakened postural muscles can improve cervical alignment (9,12,13). A plausible explanation is that movement quality during unsupervised, home-based sessions could not be verified, and suboptimal exercise technique may have attenuated the postural benefit observed under the directly supervised conditions of prior studies using similar protocols. Alternatively, the uniform improvement across all 3 Groups (that includes the education-only Control Group) may reflect a Hawthorne effect from repeated photographic assessment, natural fluctuation in habitual neck posture, or a measurement artifact related to CVA's sensitivity to momentary head position at the time of image capture. Given that CVA was the primary, power-defining outcome of this study, this null between-group finding warrants cautious interpretation and should be prioritized for methodological refinement (e.g., supervised or video-monitored sessions) in future work.

FHP has been associated with anterior displacement of the body's center of gravity and concomitant alterations in spinal and pelvic alignment (8). The present findings extend this concept by suggesting that a corrective exercise program directed primarily at cervical and scapular muscular imbalance may also be accompanied by measurable changes in pelvic alignment. Both corrective “exercise” Groups showed significant reductions in pelvic tilt; whereas, the posture education Group showed little change. Notably, baseline pelvic tilt values in the present sample fell within the normal reference range (17); the observed post-intervention decrease therefore reflects a small posterior-directed shift within normal limits, rather than correction of an overtly pathological anterior pelvic tilt. This finding may nonetheless carry physiological relevance. Anterior pelvic tilt is typically maintained by relative tightness of the hip flexors and lumbar erector spinae opposed by activation of the abdominal and gluteal musculature (17); a posterior shift in tilt following an exercise program targeting the deep cervical flexors, scapular retractors, and thoracic extensors suggests that postural correction initiated at the cervicothoracic region may propagate caudally through the myofascial kinetic chain (e.g., via the thoracolumbar fascia and posterior postural sling), subtly re-tensioning the trunk and lumbopelvic segment even though these muscles were not directly targeted by the protocol.

Increasingly sedentary behavior (including prolonged smartphone use in sustained flexed postures) may predispose individuals to heightened muscle tenderness and reduced PPT in the absence of corrective intervention (15), which is a pattern reflected in the largely unchanged or declining PPT values observed in the Control Group. The “corrective exercise” program,

which incorporated stretching of the suboccipital, pectoralis major, and upper trapezius muscles alongside strengthening of the deep cervical flexors, scapular retractors, and thoracic extensors, was effective in improving PPT across time, and is consistent with previous corrective-exercise research addressing muscular imbalance associated with FHP (9,12). However, training surface appeared to confer little additional benefit for muscle tenderness, as improvements were comparable between the CE+HARD and CE+FOAM Groups.

NDI-TH scores decreased following intervention in both corrective exercise Groups, while the “posture education” Group showed no comparable improvement. This finding aligns with previous reports that corrective exercise can reduce symptom burden and improve functional capacity in individuals with postural abnormalities (9,12,13). However, baseline NDI-TH scores differed considerably among the 3 Groups in the present dataset; consequently, the magnitude of within-group score reduction should be interpreted cautiously, and a numerically larger change in one group should not by itself be taken as evidence of superior treatment efficacy.

A similar pattern was observed for manual muscle strength, which is consistent with previous studies that demonstrated substantial strength gains following corrective exercise (1,4,19). A superior strength gain was observed only for the right lower trapezius in the CE+FOAM Group relative to CE+HARD, with no corresponding surface-dependent advantage in the remaining muscles tested. The basis for this isolated, asymmetric finding is unclear and may reflect measurement variability, dominant-limb effects, or a genuine but muscle-specific interaction between unstable-surface perturbation and neuromuscular recruitment, which warrants further investigation in future studies specifically designed to test surface-dependent strength adaptations.

Surprisingly, TUG performance remained unchanged in all 3 Groups. This finding diverges from previous reports that unstable-surface training can enhance postural control and functional mobility in older adults (11,22). A plausible explanation within the context of the present protocol is that the foam surface was embedded within a corrective exercise program focused primarily on postural realignment rather than employed as a stand-alone, task-specific balance or mobility intervention. Moreover, the prescribed exercises were predominantly static rather than dynamically perturbative, and a static foam surface alone may provide insufficient proprioceptive challenge to elicit measurable gains in dynamic functional mobility. Therefore, the present data do not demonstrate an additional benefit of foam surface corrective exercise on TUG performance relative to a stable surface exercise or posture education alone. Notably, mean TUG times in this sample were 6-7 seconds that exceeds normative values reported for healthy community-dwelling older adults (21). This finding may indicate that the participants' baseline mobility status, rather than the intervention itself, constrained the potential for measurable improvement, or that a ceiling/floor effect limited responsiveness to a purely postural (non-task-specific) intervention.

Clinical Implications

Taken together, the observed improvements in PPT, muscle strength, pelvic tilt angle, and NDI-TH appear attributable primarily to the corrective exercise itself rather than the training surface, which suggests that a foam surface may not be a necessary component when the primary treatment goal is postural and symptom correction. Nonetheless, foam surface training may hold particular value for older adults with pre-existing balance impairment, for whom the added

proprioceptive challenge could provide supplementary benefit beyond that captured by the present outcome set.

Limitations in this Study

Several limitations should be considered when interpreting the findings. First, the participants in this study were ambulatory and did not present with significant baseline balance impairment. Therefore, the findings cannot be generalized to older adults with lower functional status or clinically poor balance. Second, the exercise protocol did not incorporate progressive overload or advancing perturbation challenge, which may be necessary when postural control and dynamic balance are the primary treatment targets. Third, habitual physical activity levels and sustained postural habits (e.g., daily sitting or smartphone use duration) were not monitored and may have confounded the observed adaptations. Fourth, the home-based nature of the intervention precluded direct supervision of exercise technique, introducing potential variability in movement quality that may have influenced outcomes, particularly CVA.

CONCLUSIONS

Six weeks of corrective exercise performed on stable or foam surfaces produced significant improvements in pressure pain threshold, muscle strength, pelvic tilt angle, and cervical disability in older adults with FHP, despite the absence of corresponding changes in CVA and TUG performance. These findings support corrective exercise as a viable strategy for addressing selected pain-related and musculoskeletal outcomes in this population; whereas, the addition of a foam training surface did not confer a consistent advantage across the outcomes measured.

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Energy Expenditure and Substrate Contributions during Simulated Match Play in League Soccer Players

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ABSTRACT

Pitsamai S, Kherdkarn P, Chaunchaiyakul R, Yang AL, Chen PN, Pongkanpai B, Masodsai K. Understanding the energetic demands of match play in team sports is essential for optimizing training, performance, and recovery strategies. While total energy expenditure during match play has been investigated, limited information exists regarding the relative contributions of carbohydrate and fat oxidation during game-specific activity. Quantifying energy expenditure and substrate utilization during simulated match play may provide insights into the physiological demands placed on league soccer players. The purpose of this study was to quantify total energy expenditure and types of energy substrate contributed during the simulated match play in male soccer players. Forty-four male soccer players from Thailand League Division 3 participated in the simulated match play using the modified Loughborough Intermittent Shuttle Test (LIST). Cardiovascular, respiratory functions, ratings of perceived exertion, and metabolic contribution were obtained throughout the study period. The results showed that carbohydrate utilization increased significantly across all phases ($P < 0.05$), reaching its peak during the middle of the first half. In contrast, fat contribution decreased progressively throughout the phases ($P < 0.05$), with the lowest values observed during minutes 30-45 of the first half. Protein contribution remained minimal overall but exhibited a small yet significant increase during the last 15-minute ($P < 0.05$). All physiologic stress appears in the first quarter of soccer simulation, with the highest percent shift towards carbohydrate-based and minimal fat-based contributions on energy metabolism. This confidentially indicates the major role of glycogen storage to meet energetic demands during the games. The extremely high metabolic requirements are due to sudden and vigorous changes in body motion.

Key Words: Energy Expenditure, Energy Liberation, Glycolysis, Metabolic Pathways, Soccer Imitation

INTRODUCTION

Soccer, a high intensity intermittent sport, features critical events superimposed on varying physiologic and metabolic demands according to the type of energy substrates needed and the duration of the competition (21). Within a match of the professional level of English FA Premier League, the players perform more than 1,200 unpredictable activities to changes in direction of about ~700 turns and 30 to 40 tackles and jumps during a game (10), which covers a running distance of approximately 9 to 13 km (4, 12) with the average speed of 20 km/h to cover about 60 sprints (7). Even though, the variations in performance demands may vary with position of soccer players and ranking, the above numbers are used as the guidelines for training (57). From an energy perspective, soccer involves both aerobic and anaerobic processes that is indicated by anaerobic threshold (37). Peak performance generally appears within the initial 15-min period during a soccer match that progressively declines thereafter in either distance covered or speed (36, 38). Analysis obtained from a semi-automatic multiple camera system of 792 soccer players in German Bundesliga matches showed an average of 24.2% reduction in performance among all positions (30). Furthermore, studies in the top soccer teams indicate that the more serious reduction in the highest running performance is during the first 8 minutes of the second half (30), which is likely due to the depletion of muscle glycogen storages (45). Thus, the players employ conscious or subconscious pacing strategies to complete the match (11). Controversially, one study indicated no effects of match outcome, match location, team, and opponent quality on total distance (TD) and high-intensity running (HIR) for players in all positions (36). On the other hand, a study in 2018 indicated that the decline in players' match running performance was substantially amplified by a proven increase in game interruptions (30).

Methods of exploring performance in soccer players used the technologically advanced motion analysis systems (i.e., optical tracking systems, global and local positioning systems) (17). A field-based method included analysis of match running performance (MRP), such as the total distance covered and distances covered in various speed zones (i.e., alternated actions of walking, jogging, running, high-intensity running, and sprinting (8, 49). Regarding quantifying energy expenditure (EE) in soccer players, most previous estimations relied on accelerometers or global positioning systems (GPS) (39, 52). An investigation reported the underestimation of GPS tracking system, this may not accurately estimate EE in field sport movements or over an exercise session consisting of mixed locomotor activities interspersed with recovery periods (15). Few investigations had been focused on doubly labeled water (DLW) (13). The uses of ^2H and ^{18}O isotopes' side effects can arise from the experimental procedures, which can lead to measurement errors, as well as, high cost and the technical expertise needed for isotope ratio mass spectrometry (9). It has been proposed for the reliability, accuracy and validity of indirect calorimetry using a portable gas analyzers for measuring energy expenditure in sports to quantify oxygen consumption (VO_2), carbon dioxide production (VCO_2) at rest (40), during treadmill running in the laboratory (20), during badminton games, (23) and during post-exercise model (53).

To optimally perform soccer training, the recommended minimal amount of energy intake (EI) with high various of about 195 ± 36 kJ/kg, which derived from carbohydrate (6.0 ± 1.1 g/kg), and protein (2.2 ± 0.5 g/kg) (18), with 30 kcal/kg fat-free mass (FFM)/day in other sports training (16). This amount may not be appropriate for elite soccer players in the high tactical game (32). Over the last few decades, several investigations have been reported on aspects of soccer via the balance of energy expenditure and nutrition requirements in soccer players (27, 32). The

general characteristics of fluctuations between repeated high and low intensity during the game compulsorily induce the need for optimal nutritional strategies to offset during the first and second half of the full match. This is based on the crucial belief that meals for soccer players in professional league are appropriately prepared (22). The aim of the present study is to quantify total energy expenditure and types of energy substrate being contributed during the simulated match play in male soccer players.

METHODS

Subjects

Forty-four male soccer players from Division 3, Thailand Soccer League who met the **Inclusion Criteria** that included: (a) ages between 18 and 25 years old; (b) regular participation in competitive soccer games; (c) no recent musculoskeletal injuries; (d) no cardiorespiratory problems; and (e) not taking any medications or supplements that may influence the cardiorespiratory system, metabolism, or exercise performance. The participants underwent physical examinations and completed the Physical Activity Readiness Questionnaire (PAR-Q). They were instructed to maintain their regular diets, drink water freely, refrain from vigorous physical activity, avoid sports drinks, tea, coffee, and alcoholic beverages, and sleep for at least 8 to 10 hours for consecutive 2 days before the scheduled test date. They were also asked to record their food and fluid intakes, including the portion sizes of all foods consumed and the volume of all fluids consumed on the 3-day prior to each trial in order to estimate their nutritional status using INMUCAL program (Version 4.0, Institute of Nutrition, Mahidol University, Thailand).

Procedures

This study was ethically approved by the Ethics Committee of the Chulalongkorn University, Thailand (COA No. 650071). The study was conducted in the soccer field of a football club in Bangkok, Thailand during an off-season period. The participants signed the consent form, then anthropometric data were measured using a bioelectrical impedance analyzer (BIA, Model HBF-375; Omron, Japan) including body mass, height, body fat percentage, lean mass, visceral fat, and basal metabolic rate (BMR), and body mass index (BMI). Resting blood pressure and heart rate were determined using an automated sphygmomanometer (Model HEM-9200T, Omron, Japan). Hydration status was indirectly monitored using urine-specific gravity measured with a refractometer (USG; Refractometer DIP; model PEN-PRO; Atago, Tokyo, Japan). Blood samples from fingertips were collected under sterile techniques for baseline glucose and lactate levels (Accu-check Guide, Roche, Switzerland; Lactate Plus Meter, Lactate Plus, USA). Telemetry heart rates (Polar H-10, Polar Electro, Switzerland) and breath-by-breath gas analysis (METAMAX 3B, Cortex, German) were continuously recorded at rest, during, and post-exercises of the first and second half periods. Body mass loss was calculated from the difference between pre- and post-exercises.

Data Collection

The exercise protocol used was a modified Loughborough Intermittent Shuttle Test (LIST), which was conducted on a natural turf outdoor soccer field (31). On the first half, the participants completed 3 sets of 15 minutes of repeated activities (named as S1, S2 and S3) that included running, walking, jogging, and sprinting between 20-meter landmarks, separated by a 3-minute seated recovery between sets. During the 15-minute recovery period, all players were provided with the same amount of 150 ml electrolyte-based drink, 25 g of glucose, and *ad-libitum* of regular water. After that, performance in the second half was conducted

continuously with repeated intermittent sprinting and jogging between 20-meter landmarks until fatigue. Ratings of perceived exertion (RPE) on a scale of 0-10 were obtained throughout the period as a subjective evaluation of exertion. Termination criteria were set when subject reached one of these following criteria: (a) plateau in oxygen uptake (VO_2) despite increasing workload (≤ 150 ml/min increase); (b) heart rate ≥ 90 -95% of age-predicted HRmax; or (c) respiratory exchange ratio (RER) ≥ 1.15 as well as voluntarily stops.

Statistical Analyses

All the data were presented as the mean and standard error of mean (SEM). The data were analyzed using one-way repeated-measure ANOVA with LSD *post-hoc* test using SPSS statistical package (version 23; SPSS, Inc., New York, USA). Statistical significances were accepted when $P < 0.05$.

RESULTS

Baseline Characteristics

The average ages, mean body height, body mass and BMI were 20.06 ± 1.67 years, 175.26 ± 6.03 cm, 69.60 ± 8.17 kg, 22.61 ± 1.91 kg/m² respectively, with the averaged body fat of $15.43 \pm 4.02\%$, and the muscle mass of 36.65 ± 1.42 kg. Resting cardiovascular variables indicated normal physiological status with systolic blood pressure of 121.72 ± 8.88 mmHg, diastolic blood pressure of 70.03 ± 10.88 mmHg, and resting heart rate of 72.29 ± 8.35 bpm. Body weight loss, between rest and during half-time, was 1.42 ± 0.08 kg. Fluid ingested, ad libitum from water and same type of sports drink, during half-time were 601.3 ± 25.65 ml. All the subjects completed the S1, S2 and S3 phases. They performed 103.00 ± 3.38 min of the second half due to termination criteria of volitional exhaustion ($n = 17$), plateau in VO_2 ($n = 12$), approaching target heart rate ($n = 6$), and $\text{RPE} > 1.15$ ($n = 9$).

Respiratory Responses during Simulated Match Play

Minute ventilation ($\dot{V}_E$, Figure 1A) showed a significant increase from resting condition (rest-S1, $P < 0.05$), with steadily and significantly rose across all successive stages of S1-S2 ($P < 0.05$), S2-S3 ($P < 0.05$), S3-exhaustion ($P < 0.05$). Tidal volume (V_T , Figure 1B) showed a significant increase from rest (rest-S1, $P < 0.05$) and reached a plateau since then, with no further significant increase ($P > 0.05$) throughout the studying period. Respiratory rate (RR, Figure 1C) increased progressively throughout the exercise protocol, with significant differences from resting condition (rest-S1, $P < 0.05$), between S1-S2 ($P < 0.05$), S2-S3 ($P < 0.05$), S3-exhaustion ($P < 0.05$).

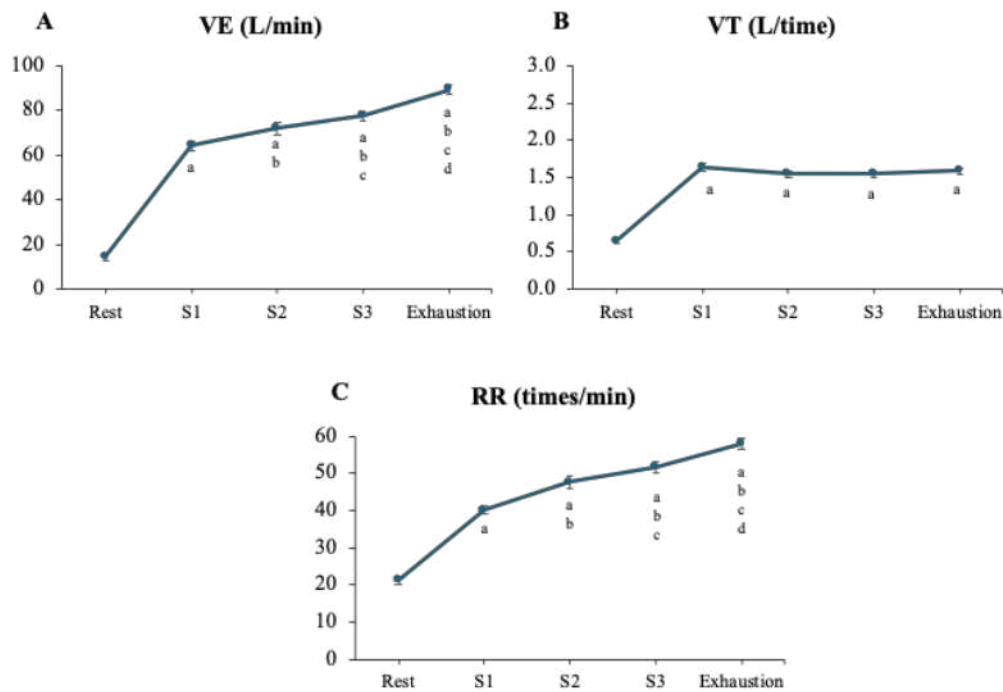


Figure 1. Respiratory responses of minute ventilation ($\dot{V}_E$), tidal volume (VT), and respiratory rate (RR) during a modified Loughborough Intermittent Shuttle Test (LIST). Value are means and SEM: (a) significant difference from rest; (b) significant difference from S1; (c) significant difference from S2; (d) significant difference from S3.

Metabolic Responses during Simulated Match Play

Indirect calorimetry variables, $\dot{V}O_2$ and $\dot{V}CO_2$, were continuously monitored to represent metabolic responses (Figure 2). From resting conditions, $\dot{V}O_2$ and $\dot{V}CO_2$, in both absolute and relative units, increased significantly during S1 ($P < 0.05$), with dropped during S2 ($P < 0.05$) and S3 ($P < 0.05$) then approaching their peaks during the exhaustive exercise stage ($P < 0.05$). From resting condition, respiratory exchange ratio (RER) showed steady increase in S1 ($P < 0.05$), S2 ($P < 0.05$) and S3 ($P < 0.05$), then progressively increased during exhaustive stage ($P < 0.05$).

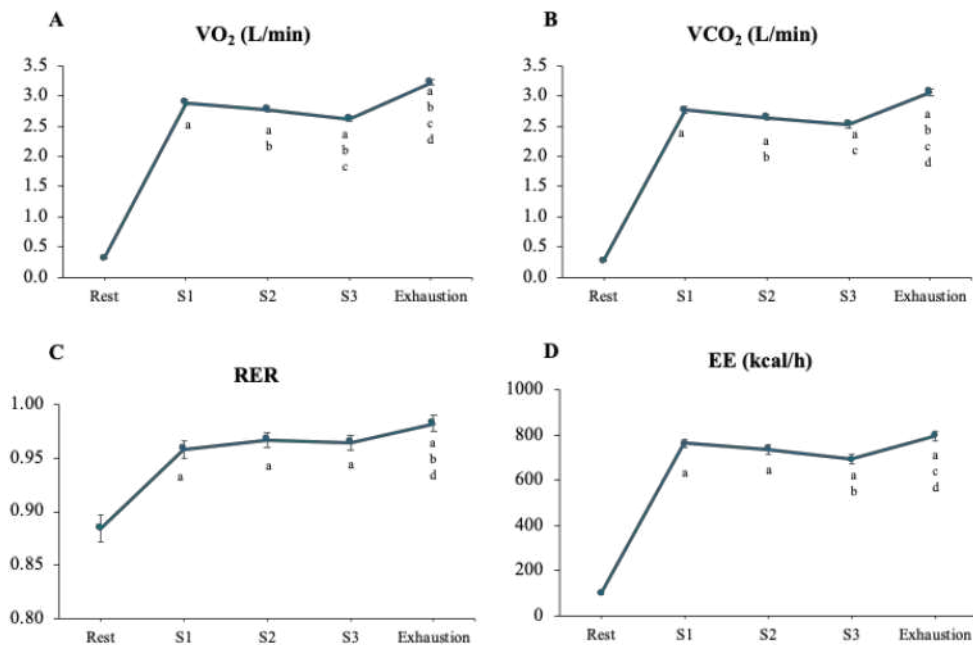


Figure 2. Metabolic and energetic responses of the absolute oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER), and energy expenditure (EE) during a modified Loughborough Intermittent Shuttle Test (LIST). Value are means and SEM. (a) significant difference from rest; (b) significant difference from S1; (c) significant difference from S2; (d) significant difference from S3.

Energy Expenditures and Substrate Contributions

Estimated energy expenditures (kcal/h) from all three macronutrients (Figure 3A) increased significantly from resting ($P < 0.05$). Compared to resting condition, carbohydrates (CHO) significantly increased at S1 and throughout the studying phases ($P < 0.05$), then significantly lower than other phases at S3 ($P < 0.05$), where the significantly highest at exhaustion ($P < 0.05$). Fat and protein (PRO) showed a consistent increase from resting condition throughout the entire phases ($P < 0.05$). Similarly to CHO, PRO exerted the lowest at S3 ($P < 0.05$) and peak at exhaustion ($P < 0.05$).

To demonstrated energy distributions from three macronutrients, data were reanalyzed in term of percentages (Figure 3B). Compared to resting level, carbohydrate (CHO) utilization increased markedly throughout all phases ($P < 0.05$), where peak appeared at S2. Fat (FAT) contribution declined progressively throughout all phases ($P < 0.05$), with peaks at S2 and S3. Protein (PRO) contribution remained at minimal level but showed a slight elevation during S3 ($P < 0.05$).

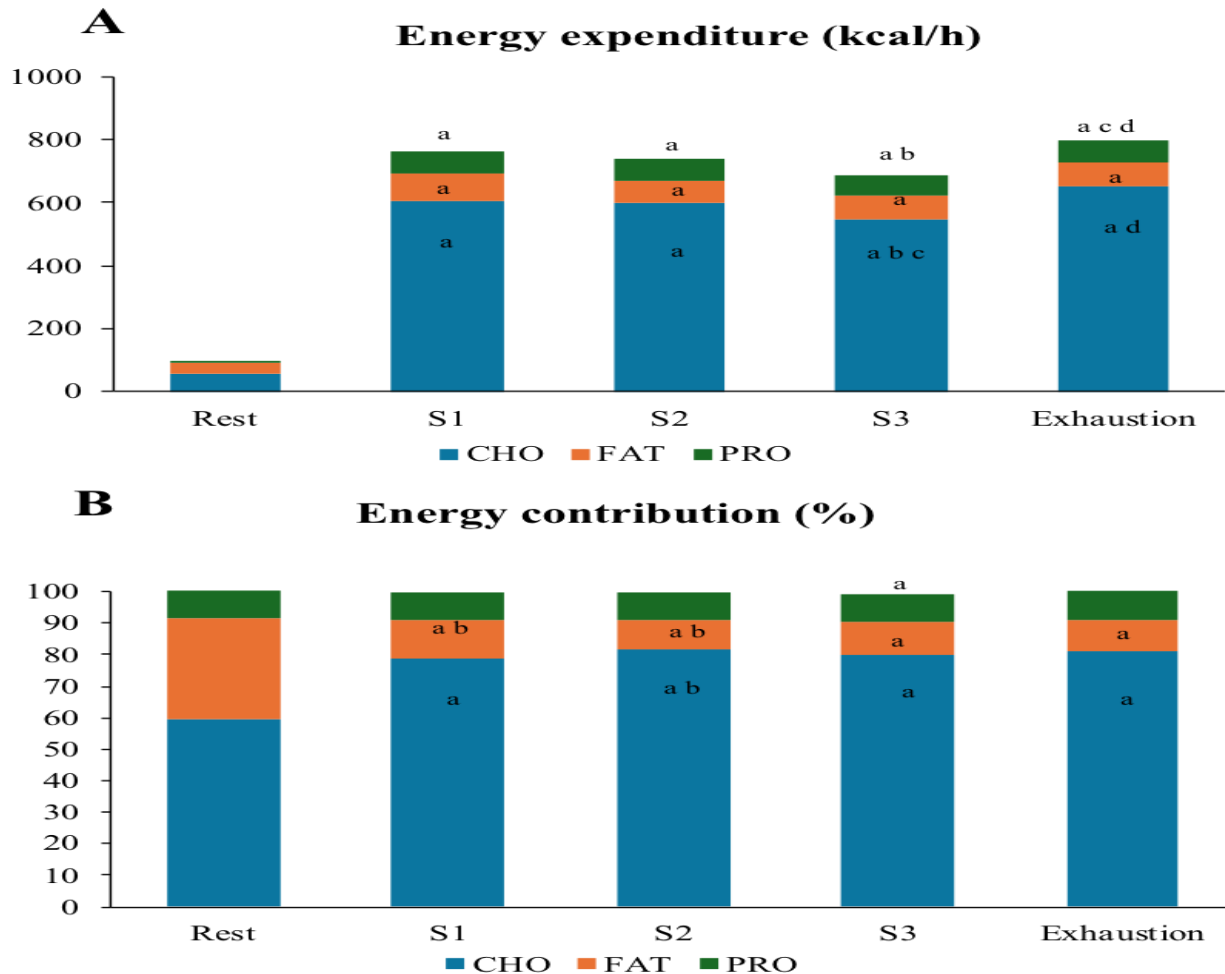


Figure 3. Changes of energy expenditures from different macronutrients (A) and % of substrate energy contributions (B) of carbohydrate (CHO), protein (PRO), or fat (FAT) during a modified Loughborough Intermittent Shuttle Test (LIST). Value are means and SEM. (a) significant difference from rest; (b) significant difference from S1; (c) significant difference from S2; (d) significant difference from S3.

DISCUSSION

The present study quantifies the predictions of energy substrates being utilized in metabolic processes in soccer players during a simulated soccer match play for the first and second half. Metabolic demands show plateaus of VO_2 , VCO_2 , RER, and EE since the first quarter (S1) of the first half, in which the highest responses are at exhaustion during the second half. Increases were noted in substrates utilization and energy contribution derived from all three macronutrients since S1, in which highest is from CHO and certain percentages from FAT, but not from PRO. The limited contributions of CHO since S1 reflects the substantial decline of physical performance after the first 15-min of soccer game had been previously identified (36, 38), with remarkable decline during the eight minutes of the second half (30). This study demonstrates main energy distributions are derived from three macronutrients, but in different magnitudes along the simulated match-play period. Data, in term of percentages, show the remarkable roles of carbohydrate (CHO) utilization throughout all phases, with initial

adjustment during S1 with peak at S2. Fat (FAT) contribution declined progressively throughout all phases, with peaks at S2 and S3. Protein (PRO) contribution remained at minimal level but showed a slight elevation during S3. These data confirm a predominant reliance of carbohydrate metabolism during high-intensity intermittent exercise, with fat oxidation contributing primarily at the end of the first half.

Indirect calorimetry is generally used as a method to identify aerobic and anaerobic energy contributions during sports events (3). Metabolic demands during exercise will induce fluctuations of $\dot{V}CO_2$ and $\dot{V}O_2$, which shift RER of about 0.8-0.9 in S1, S2, and S3. At the exhaustive condition, RER indicates an upward shift toward carbohydrate utilization. At intense exercise, RER approaches 1.0 and may be up to 1.2, this implies the less oxidative efficiency, in which anaerobic condition will take place.

It has long been recognized that carbohydrate and fat serve as energy substrates at rest and during exercise. The relative contribution of both substrates depends on age, gender, fiber type, blood free-fatty acids, exercise duration and intensity and ratio of macronutrients intake during pre-exercise (2, 26, 27, 41). Carbohydrate metabolism is of importance during prolonged exercise, reflecting the critical role of glucose regulation, assuring optimal blood glucose level, proper muscle fueling and delaying the onset of muscle fatigue (19). Fat metabolism represents a secondary sustainable source of energy to meet the extensive demands, which preserve when carbohydrate storage becomes limited (2). Protein can be utilized as an energy substrate in certain extreme conditions like break down of leucine for fuel, conversion of glutamine/alanine for glucose transport (glucose-alanine cycle) and low carbohydrate intake (43). Recently, Mekonen et al. indicated the uptake of amino acids from plasma bed at low intensity of exercise which plays a role on oxidative gluconeogenesis during recovery (34).

Energy production during continuous, submaximal exercise is primarily produced through oxidative phosphorylation or the oxidation of carbohydrates and fats. As exercise intensity increases towards exhaustive levels, the body gradually relies more and more on anaerobic energy production processes to meet the higher metabolic demand (51). Traditionally, aerobic energy liberation has been determined by measuring oxygen consumption. For a few decades, researchers have evaluated oxygen uptake and oxygen deficit to determine the onset of anaerobic process (25). There is no precise determinant when aerobic will cease or anaerobic contribution will take place during exercise. We only recognize that these shifting processes give the clue for pre-fatigue conditions. Onsets of aerobic and anaerobic contribution vary with exercise duration and intensity. For example, Medbo and Tabata (1989) demonstrated the progressive increase of oxygen consumptions during three minutes cycling (33). Shiraki et al (2020) indicated no different contributions of aerobic/anaerobic ratio among 7 repeated short-intense exercises (50). Accordingly, recent investigation reported that RER and factors known to affect substrate utilization during exercise, such as age, gender, exercise intensity and duration, fitness level and daily dietary intake, all together explain ~ 59% during exercise in elite cyclists (47). The marked elevation in $\dot{V}O_2$ and energy expenditure across the LIST indicates a substantial aerobic energy contribution, exceeding 12 METs during peak phases consistent with data from other competitive match play (46). The rise in RER (>1.0) reflects increasing carbohydrate reliance as exercise intensity escalates (46). This transition aligns with prior findings showing that soccer players predominantly depend on glycolytic pathways during repeated sprint activity, supported by high aerobic recovery capacity between bouts (6, 28).

The underlying reasons for the decline of running performance were proposed for different reasons. For example, the frequency of game interruption (30), glycogen depletion (6). Moreover, blood glucose levels at rest and during exercises are 109.05 ± 2.40 , 126.27 ± 3.29 (end of the first half) and 103.00 ± 3.38 mg/dL respectively. The quantitated pre-test meals were 741 ± 328 kcal. Whereas weight losses and fluid intakes are 1.42 ± 0.08 kg and 601.31 ± 25.65 ml respectively. The decline of performance within this study is, therefore, most likely a reflection of substrates utilized during the simulated match play.

The progressive rise in ventilation during the simulated match is primarily driven by breathing frequency. Peak $\dot{V}_E$, as indicator of high ventilatory demand (Figure 2), were observed during the final bouts, corresponding to approximately six-folds increase from resting ventilation. Similar patterns of $\dot{V}_E$ and RR responses throughout the entire period of the study, whereas $\dot{V}_T$ reaches its plateau since the first 15-minute stage. This suggests that an initial, low-to-moderate exercise intensity, ventilatory response primarily due to increase in tidal volume. At higher intensity, further increases in ventilation are mainly driven by increases in RR (29).

Soccer contains high uncertainty of actions and contacts during the games. It is a high demands physical performance sports, which encompasses a wide range of physical demands, including short and long sprints, agility, rapid changes in direction, tackling, jumping, and kicking the ball. The present study collected data at 85-90% of their age predicted maximum heart rate. Numerous high intensity training regimens have been implanted to improve players' performance. For example, this sport is normally trained at $\pm 85\%$ 1RM in conventional strength training, with protocols with concentric, eccentric or plyometric exercises, in all planes of movement (48). Jon Hoff et al. (2002) reported the effectiveness of high intensity training for 3-8 minutes at 85-95% of maximum heart rate to improve aerobic capacity in soccer players (1). It was documented that performances primarily vary according to the different playing positions of the players due to their different duties during the competition (1). However, it is a matter of fact that scientists quantify soccer players using the same running performance method (5). Reliability of a field-study in soccer players was reported in 2022 (36) indicated the remarkable match running performance (MRP) in the first quarter with the lowest declined MRP in the last quarter of the six 15-minute periods. Monitoring of changes of energy expenditure in field sports have become an indispensable part of training and matches. During the last few years, several validation studies on the metabolic power model in intermittent sports were conducted and summarized within a recently published systematic review (35). The present study sets up the same repeated field-based jogging-running-sprinting according to the Loughborough Intermittent Shuttle Test (LIST). Moreover, benefits of the same field-based test in soccer players are that we can mainly focus on the aspect of physical performance derived from same physical stress without/with less concerning on perceived effort, tactical behaviors and players positions (44, 55). LIST is a well-established as a valid lab test simulating soccer match demands, featuring repeated high-intensity shuttles (walking, max sprints, moderate/high-intensity runs) over 90 minutes, measuring physiological responses like heart rate, lactate, and energy expenditure, nutritional, hydration, and performance studies, with recent research often focusing on specific interventions (like carbs/fluids) or comparing it to real match play to understand soccer's unique demands (31).

While the majority of a soccer game relies on aerobic metabolism, occasionally during specific high-intensity moments heavily tax the anaerobic system. Thus, the ratio of aerobic to anaerobic capacity in soccer players, as well as in other sports, is not a fixed universal number, but these variables are of interest among scientists. Previous investigations explored aerobic

(from gas analyzer) and anaerobic capacity (from field test of Running Anaerobic Sprint Test-RAST). Results showed fluctuations in anaerobic variables (24, 54). The more precise differentiation between the shifting onsets of anaerobic and aerobic processes was previously performed with gas analyzer and compulsorily requires the parallel changes on level of blood chemistry (23). The above could be done in some sports, which had to frequently stopped the games for blood samplings, and prediction based on mathematical calculation.

The validity of gas analyzers (metabolic carts/indirect calorimeters) for measuring substrate contributions during exercise is generally considered the gold standard for whole-body substrate metabolism (14, 42). However, the accuracy is highly dependent on the device types, rigorous calibration, and the specific exercise intensity being measured (56). Previous study reported that the portable gas analyzer produced acceptably stable and reliable results both in simulated and human trials (31).

The pattern of substrate utilization and shifting observed here are critical for maintaining power output and speed during intermittent efforts. These findings emphasize that soccer players rely heavily on glycogen stores to meet energetic demands, highlighting the importance of carbohydrate availability before and during matches to prevent performance decrements and fatigue. Understanding these integrated physiological responses provides actionable insights for conditioning, nutrition. Training programs should target both aerobic capacity (for recovery efficiency) and anaerobic power (for high-intensity bursts). From a nutritional perspective, ensuring sufficient pre-match glycogen loading and intra-match carbohydrate intake can sustain energy availability and delay fatigue. These findings provide an evidence-based framework for training prescription, nutritional strategies, and recovery optimization in competitive soccer.

CONCLUSIONS

All physiologic stress appears in the first quarter of soccer simulation showing the highest % shift toward carbohydrate-based and minimal fat-based contributions on energy metabolism. This confidentially indicates the major role of glycogen storages to meet energetic demands during the games. The extremely high metabolic requirements are due to sudden and vigorous changes in body motion. CHO remains the main energy substrate contribution throughout the entire match-play simulation. FAT plays a secondary energy contribution, whereas PRO plays a minor role. This study, partly, solves the challenge to optimize training protocol for soccer players. Training and meals composition which should be focused during training period. It is even better if any training can maintain aerobic or anaerobic performance within the game.

CONFLICTS OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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Advances in β -Alanine Delivery: Mechanisms of Absorption, Plasma Kinetics, and Reduced Paresthesia

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ABSTRACT

Vasenina E, Mallett GS, Kurtz JA, Leung W, Antonio B, Antonio J. Advances in β -Alanine Delivery: Mechanisms of Absorption, Plasma Kinetics, and Reduced Paresthesia. β -Alanine (BA) is a non-essential amino acid that serves as the rate-limiting precursor for the synthesis of carnosine (β -alanyl-L-histidine), a histidine-containing dipeptide concentrated in skeletal muscle that contributes to intracellular pH buffering, antioxidant defense, anti-glycation activity, and modulation of contractile function. Oral BA supplementation reliably increases muscle carnosine concentrations and produces small but meaningful improvements in high-intensity exercise performance. However, conventional immediate-release formulations are limited by rapid plasma kinetics that produce transient paresthesia, mediated through activation of cutaneous Mas-related G-protein-coupled receptor D (MrgprD) by circulating BA. The dose-dependent nature of paresthesia constrains acute dosing and necessitates frequent split dosing, which can compromise long-term adherence. This narrative review summarizes the physiological roles of BA and carnosine, the transporter-mediated mechanisms governing intestinal absorption and skeletal muscle uptake, the plasma pharmacokinetics of conventional BA supplementation, and recent advances in delivery technologies (including sustained-release tablets, modified-release capsules and powders, and emerging encapsulation systems) that aim to optimize systemic exposure while attenuating peak plasma concentrations. We also discuss strategies to reduce paresthesia, the practical implications of these advances for athletic performance and clinical applications, and priority directions for future research.

Key Words: β -Alanine, Carnosine, Paresthesia, Sustained-Release

INTRODUCTION

β -alanine (BA) is a non-proteinogenic, non-essential β -amino acid that has emerged as one of the most widely studied and commercially distributed ergogenic supplements in sports nutrition (22,29,58). Its physiological relevance derives almost entirely from its role as the rate-limiting precursor for the intramuscular synthesis of carnosine (β -alanyl-L-histidine), a histidine-containing dipeptide present in millimolar concentrations in human skeletal muscle (11,17,42). Carnosine contributes to several functions of importance to contracting muscle, including non-bicarbonate intracellular proton buffering, antioxidant activity, anti-glycation defense, and modulation of calcium handling within the contractile apparatus (11,20,37). Because intracellular histidine is generally available in concentrations far exceeding those required for carnosine synthesis, while circulating BA concentrations remain low under normal dietary conditions, the rate of muscle carnosine accumulation is governed primarily by BA availability (17,25,58). Accordingly, oral BA supplementation has become the principal nutritional strategy for elevating muscle carnosine and the associated downstream physiological adaptations.

Multiple meta-analyses confirm that BA supplementation produces small but consistent improvements in high-intensity exercise performance, particularly in tasks lasting between approximately 30 seconds and 10 minutes, the duration range over which intracellular acidosis exerts its greatest effect on muscular fatigue (22,29,49,51). Beyond athletic performance, interest in BA and carnosine has expanded into broader clinical and translational contexts, including age-related declines in neuromuscular function (21,37,43), metabolic disorders such as type 2 diabetes (33,39,46), and cellular protective mechanisms relevant to oxidative stress and glycation-related pathology (14,59,63). These widening applications have intensified scrutiny of how BA is delivered, how reliably it loads muscle carnosine across diverse populations, and how supplementation can be optimized for both efficacy and tolerability.

Despite its established efficacy, conventional immediate-release BA supplementation is limited by several pharmacokinetic and tolerability constraints. Following oral ingestion, plasma BA rises rapidly, typically reaching peak concentrations within 30–60 minutes, and is cleared with a relatively short half-life of approximately 25 minutes (26,52). When acute doses exceed approximately 800 mg, transient paresthesia (a tingling or pruritic sensation localized to the face, neck, and upper extremities) frequently occurs (16,18,40). This sensation is mediated by activation of cutaneous Mas-related G-protein-coupled receptor D (MrgprD) on sensory neurons by circulating BA and is independent of any direct effect on skeletal muscle (40). The severity of paresthesia is dose-dependent and tied to peak plasma concentration (C_{max}), and at single doses of 1.6 g and above, sensations are often described as unpleasant (26,52). To circumvent this constraint, conventional supplementation protocols recommend dividing total daily intake (typically 4–6 g·day⁻¹) into multiple smaller doses of 0.8–1.6 g taken several times throughout the day (44,58). Although effective, such regimens demand sustained behavioral compliance over the 4–10 weeks typically required to substantially elevate muscle carnosine, and adherence challenges represent a non-trivial limitation in both research and applied contexts (44,47).

These pharmacokinetic and adherence considerations have motivated a growing body of formulation research aimed at modulating BA absorption kinetics. Sustained-release tablets, modified-release capsules and powders, and emerging encapsulation technologies (including microencapsulation and lipid-based delivery systems) have each been investigated as means of attenuating peak plasma concentrations while preserving or enhancing total systemic

exposure (15,16,23,41). The central pharmacokinetic objective is consistent across these approaches: to slow the rate of BA appearance in plasma sufficiently to remain below the MrgprD activation threshold while sustaining circulating concentrations long enough to support efficient transporter-mediated uptake into skeletal muscle (40,47,52). Successful achievement of this profile would permit larger single doses, fewer daily administrations, improved adherence, and potentially more consistent muscle carnosine loading across responders and non-responders.

The purpose of this narrative review is to synthesize the current evidence on BA delivery and its physiological consequences. Specifically, we (i) summarize the physiological roles of BA and carnosine in skeletal muscle, (ii) examine the transporter-mediated mechanisms of BA absorption and intracellular uptake, (iii) describe the plasma pharmacokinetics of conventional supplementation and the basis of paresthesia, (iv) review recent advances in sustained-release, modified-release, and encapsulation-based delivery systems, (v) evaluate strategies to reduce paresthesia and improve adherence, and (vi) consider implications for athletic performance and clinical applications, together with priority directions for future research.

METHODS

This manuscript was conducted as a narrative review using structured literature identification and selection procedures. The primary objectives of the review were: (a) to characterize the physiological roles of β -alanine and carnosine in skeletal muscle with particular emphasis on intracellular pH buffering, antioxidant defense, anti-glycation activity, and modulation of contractile function; (b) to summarize the transporter-mediated mechanisms governing intestinal absorption and skeletal muscle uptake of β -alanine; (c) to evaluate the plasma pharmacokinetics of conventional supplementation and the basis of dose-dependent paresthesia; and (d) to synthesize current evidence on advances in delivery technologies, including sustained-release tablets, modified-release capsules and powders, and emerging encapsulation systems with specific attention to absorption kinetics, peak plasma concentrations, tolerability, and translational application to athletic and clinical populations.

A structured search of the literature was performed using electronic databases commonly utilized in biomedical, nutrition, and exercise science research, including PubMed/MEDLINE, Scopus, and Google Scholar. Searches were conducted without strict publication date limitations; however, emphasis was placed on peer-reviewed human trials, mechanistic investigations, systematic reviews, meta-analyses, and consensus statements relevant to β -alanine supplementation, muscle carnosine loading, and pharmacokinetic delivery strategies. Foundational mechanistic studies were included when necessary to contextualize biochemical and physiological pathways relevant to amino acid transport, carnosine synthesis, and sensory neuron activation.

Search terms were used individually and in combination and included β -alanine, beta-alanine, carnosine, muscle carnosine, CARNS1, carnosine synthase, ATPGD1, supplementation, pharmacokinetics, plasma kinetics, C_{max}, T_{max}, area under the curve, sustained-release, slow-release, modified-release, controlled-release, microencapsulation, lipid-based delivery, encapsulation, bioavailability, paresthesia, MrgprD, cutaneous sensory neurons, PAT1, SLC36A1, taurine transporter, TauT, SLC6A6, intracellular buffering, hydrogen ions, exercise performance, high-intensity exercise, repeated sprint, dosing strategy, adherence, and

tolerability. Reference lists of relevant articles and review papers were also screened to identify additional studies not captured in the primary search.

Studies were included if they provided mechanistic insight into β -alanine transport or carnosine biosynthesis; characterized the pharmacokinetics of oral β -alanine supplementation in human participants; evaluated the effects of conventional or modified delivery formulations on plasma kinetics, muscle carnosine content, or sensory tolerability; or examined exercise performance, clinical, or translational outcomes following β -alanine supplementation. Both randomized controlled trials and controlled experimental studies were considered, including pharmacokinetic crossover designs and longer-duration loading trials. Systematic reviews and meta-analyses were used to contextualize overall evidence strength when available, particularly for outcomes related to muscle carnosine response, exercise performance, and supplementation safety.

Exclusion criteria included non-English publications without accessible translation, abstracts lacking sufficient methodological detail, and studies in which β -alanine effects could not be isolated from multi-ingredient interventions without appropriate control groups. Animal and in vitro studies were included selectively when necessary to explain underlying mechanisms, particularly for transporter-level competition, MrgprD activation, and lipid-based delivery technologies, but were interpreted cautiously with regard to translational applicability in human supplementation contexts.

Findings were synthesized qualitatively and organized according to thematic domains aligned with the aims of the review, including the physiological roles of β -alanine and carnosine, transporter-mediated absorption and skeletal muscle uptake, plasma pharmacokinetics of traditional supplementation, advances in delivery systems, strategies to mitigate paresthesia, and implications for athletic performance and clinical applications. Emphasis was placed on mechanistic consistency, pharmacokinetic relevance, clinical applicability, and identification of current gaps in the literature requiring further investigation.

PHYSIOLOGICAL ROLES OF β -ALANINE AND CARNOSINE

Carnosine Synthesis in Skeletal Muscle

Carnosine is present in relatively high concentrations in skeletal muscle and nervous tissue, where it contributes to physiological processes relevant to fatigue resistance and cellular protection (11). In skeletal muscle, carnosine is synthesized intracellularly from β -alanine and L-histidine through the ATP-dependent enzyme carnosine synthase-1 (CARNS1) (42). Human skeletal muscle typically contains carnosine concentrations ranging from approximately 10–40 mmol·kg⁻¹ dry muscle, with average values near 20–30 mmol·kg⁻¹ dry muscle (11,17,55). These concentrations vary according to several physiological factors, including dietary habits, training status, muscle fiber composition, age, and biological sex (17,25,36,48).

Role of Carnosine Synthase

Carnosine synthesis in skeletal muscle is catalyzed by CARNS1, an ATP-dependent enzyme that condenses β -alanine and L-histidine to form carnosine. The CARNS1 enzyme belongs to the ATP-grasp enzyme family and is expressed in several tissues, with particularly high activity in skeletal muscle, where carnosine concentrations are greatest (19). This enzyme catalyzes the formation of a peptide bond between β -alanine and histidine, producing carnosine and adenosine diphosphate (ADP) as products.

Although CARNS1 is required for carnosine formation, available evidence indicates that enzymatic capacity is not the primary limitation for carnosine formation under physiological conditions. Instead, substrate availability, specifically β -alanine, largely determines the rate of carnosine formation within skeletal muscle fibers (10,58). This conclusion is supported by observations that histidine concentrations in plasma and muscle are typically sufficient to support dipeptide formation; whereas, circulating β -alanine concentrations remain relatively low under normal dietary conditions (25,58). The reported Michaelis constant (K_m) of CARNS1 for β -alanine is well above typical resting intracellular β -alanine concentrations in skeletal muscle (19), which means that intracellular β -alanine availability, rather than enzymatic capacity, is rate-limiting for carnosine synthesis even when systemic delivery appears adequate. This kinetic relationship may contribute to the inter-individual variability in carnosine response to supplementation observed across controlled trials (48), although direct human data linking intracellular β -alanine concentrations to individual differences in carnosine accumulation remain limited.

Rate-Limiting Role of β -Alanine

The rate-limiting role of β -alanine has important implications for sports nutrition. Dietary β -alanine intake from natural food sources is relatively low because the amino acid is primarily consumed through carnosine-containing animal products. Consequently, supplementation represents the most effective strategy for increasing muscle carnosine concentration.

Several lines of evidence support the role of β -alanine as the rate-limiting substrate for carnosine synthesis. Plasma histidine concentrations typically range from 50 to 100 micromolar (μM); whereas, circulating β -alanine concentrations are generally $<2 \mu M$, indicating that histidine availability rarely limits enzymatic activity (17). Experimental studies demonstrate that increasing β -alanine availability through oral supplementation markedly elevates intramuscular carnosine concentrations, typically by 40–80% after 4–10 weeks of supplementation (17,27,53).

Early investigations demonstrated that oral β -alanine supplementation significantly increased muscle carnosine concentrations, providing direct evidence that β -alanine availability regulates carnosine synthesis (27). Subsequent systematic reviews and meta-analyses confirm that β -alanine supplementation reliably increases muscle carnosine across diverse populations, with near-universal responsiveness when adequate dosing protocols are used (22,48). These increases accumulate progressively during supplementation, reflecting the gradual nature of intracellular dipeptide synthesis and storage.

Functional Roles of Muscle Carnosine

Carnosine is a multifunctional dipeptide highly concentrated in skeletal muscle and excitable tissues. Although its role in intracellular buffering during high-intensity exercise is the most widely studied function (17,42), evidence suggests that carnosine also contributes to antioxidant defense (34), protection against protein glycation (6), and neuromuscular function and aging (37). These diverse functions are largely attributed to the biochemical properties of the histidine imidazole ring and the molecule's capacity to interact with reactive metabolites and metal ions. Collectively, these mechanisms suggest that carnosine contributes not only to exercise performance but also to cellular protection and metabolic regulation within skeletal muscle.

Intramuscular Buffering

The primary physiological function of carnosine in skeletal muscle is intracellular acid-base buffering. During high-intensity exercise, rapid ATP turnover and increased glycolytic flux leads to the accumulation of hydrogen ions (H^+) that result in a reduction in intracellular pH (24). Intracellular acidosis can impair cross-bridge cycling, reduce Ca^{2+} sensitivity of the contractile apparatus, and inhibit key metabolic enzymes that ultimately contributes to muscular fatigue (20,37).

Carnosine functions as an effective intracellular proton buffer due to the imidazole ring of its histidine residue, which has a pKa of approximately 6.83, which is close to the physiological pH range experienced during intense exercise (1,37). This property allows carnosine to accept protons and attenuate decreases in intracellular pH during periods of high metabolic stress. Consequently, carnosine contributes substantially to the non-bicarbonate buffering capacity of muscle tissue (17).

Increases in muscle carnosine following β -alanine supplementation have been associated with improvements in high-intensity exercise performance, particularly during activities that last approximately 30 seconds to 10 minutes, where metabolic acidosis is a key contributor to fatigue (17,50,61). Meta-analyses report small but significant improvements in exercise capacity following β -alanine supplementation that supports the role of enhanced intracellular buffering capacity in mediating these ergogenic effects (49,51). The relationship between supplementation dose, muscle carnosine accumulation, and exercise outcomes is broadly dose-dependent: higher daily β -alanine intake within the typical supplemental range produces greater muscle carnosine elevation, which in turn corresponds with the magnitude of improvement in buffering-limited performance tasks (44,48,50,58). The mechanistic and ergogenic implications of this dose-response relationship are developed further in the Athletic Performance section.

Antioxidant Activity

In addition to its buffering capacity, carnosine exhibits antioxidant properties that may contribute to cellular protection during exercise-induced oxidative stress (OS) (37). Skeletal muscle contractions increase the production of reactive oxygen species (ROS) and reactive nitrogen species (RNS), which can damage proteins, lipids, and deoxyribonucleic acid if not adequately neutralized (62,64).

Studies demonstrate that carnosine can scavenge ROS and reactive carbonyl (RC) compounds, thereby limiting oxidative damage within muscle cells (2). Carnosine also acts as a metal-ion chelator, particularly for transition metals such as copper and zinc that potentially reduces metal-catalyzed oxidative reactions, which contribute to free radical generation (63).

Evidence further suggests that carnosine can inhibit lipid peroxidation and protect cellular membranes from oxidative damage (11,14). Although the antioxidant role of carnosine in human skeletal muscle during exercise remains an area of ongoing investigation, increased carnosine concentrations may enhance the muscle's ability to manage OS associated with repeated high-intensity contractions (12,30).

Anti-Glycation Properties

Carnosine exhibits anti-glycation activity by inhibiting the formation of advanced glycation end products (AGEs). Glycation occurs when RC compounds generated during glucose

metabolism react with proteins or lipids, forming AGEs that can impair cellular function and contribute to metabolic and age-related diseases (59).

Carnosine can act as a carbonyl scavenger by reacting with reactive aldehydes such as methylglyoxal and glyoxal, thereby limiting their interaction with cellular proteins (5). This anti-glycation activity helps to preserve protein structure and function and may reduce the accumulation of dysfunctional proteins within tissues. Studies demonstrate that carnosine can inhibit protein cross-linking and glycoxidative damage that are mechanisms implicated in aging and metabolic disease (28,33).

Although much of the research on the anti-glycation effects of carnosine has been conducted in cellular or animal models, emerging human studies suggest that β -alanine or carnosine supplementation may influence markers of glycemic control and metabolic health. Systematic reviews have reported improvements in glycemic regulation and insulin sensitivity in certain populations that suggest the potential metabolic benefits beyond exercise performance (39,46).

Potential Neuromuscular and Aging-Related Benefits

Carnosine may also influence neuromuscular function and age-related physiological processes (37). Within skeletal muscle, carnosine has been shown to increase Ca^{2+} sensitivity of myofibrillar proteins that potentially enhance force production during muscle contractions. Studies suggest that carnosine may interact with the contractile apparatus and influence Ca^{2+} handling within the sarcoplasmic reticulum, thereby affecting excitation-contraction coupling (20).

Muscle carnosine concentrations may decline with aging, potentially contributing to reductions in buffering capacity and contractile function observed in older individuals (37). Accordingly, there is growing interest in the potential role of β -alanine supplementation for supporting muscle function and exercise capacity in aging populations. Evidence indicates that increasing muscle carnosine through β -alanine supplementation may help to improve exercise capacity and fatigue resistance in older adults, although further research is required to fully elucidate these effects (21,43).

Collectively, the biochemical and physiological properties of carnosine, including intracellular buffering, antioxidant activity, anti-glycation effects, and potential neuromuscular benefits, highlight its importance for skeletal muscle physiology and provide a mechanistic basis for the performance-enhancing effects of β -alanine supplementation.

MECHANISMS OF β -ALANINE ABSORPTION AND TRANSPORT

Amino Acid Transporters

β -alanine does not have a dedicated "exclusive" transporter. Instead, it utilizes broad-specificity transport systems. The primary mediator for β -alanine uptake is the Proton-coupled Amino Acid Transporter 1 (PAT1), encoded by the SLC36A1 gene (4). PAT1 is a low-affinity, high-capacity transporter that moves small amino acids in a H^+ -dependent manner. Additionally, the Taurine Transporter (TauT), encoded by SLC6A6, also facilitates β -alanine transport that reflects the structural similarity between taurine and β -alanine, since both are beta-amino acids (4,56). Therefore, β -alanine uptake may be influenced by competition with other amino acids that share the same transport systems.

Competitive Transport with Other Amino Acids

Because β -alanine shares transport pathways with other molecules, its absorption is subject to competitive inhibition. PAT1 also transports glycine, L-proline, and L-alanine. More critically, because β -alanine is a potent substrate for TauT, high doses of β -alanine can inhibit taurine uptake due to substrate competition (56). While acute competition exists, chronic β -alanine supplementation at standard dosages (~ 3 to $6 \text{ g} \cdot \text{day}^{-1}$) does not typically lead to clinically significant taurine depletion in human skeletal muscle, although it remains a point of physiological interest in animal models (32). Since these transport systems are saturable, increasing β -alanine intake beyond a certain threshold may not proportionally enhance absorption, thus highlighting the importance of understanding the upper limits of transporter capacity.

Saturable Uptake

The transport mechanisms for β -alanine exhibit Michaelis-Menten kinetics, meaning the rate of absorption increases with the concentration of the substrate until the transporters become saturated (3,4,57). This saturable nature is a primary driver behind the "paresthesia" (tingling sensation) often reported by users. When a large bolus of β -alanine is consumed, plasma β -alanine concentrations rise rapidly and may temporarily exceed the immediate uptake capacity of skeletal muscle and other tissues due to the saturable nature of amino acid transport systems. As a result, excess circulating β -alanine can interact with peripheral sensory neurons, contributing to the transient paresthesia commonly reported following high single doses (9,16). Because skeletal muscle carnosine synthesis depends on intracellular β -alanine availability and occurs progressively over time, sustained elevations in plasma β -alanine from repeated moderate doses may more effectively support 1 in muscle carnosine concentrations compared with large acute boluses (26,31). Consequently, "divided dosing" or "sustained-release" formulations are often employed to maintain steady absorption without hitting the saturation threshold that triggers side effects, optimizing both muscle carnosine loading and tolerability in humans.

Distribution and Uptake into Muscle

Once β -alanine crosses the basolateral membrane of the enterocyte, it enters the portal circulation and is distributed throughout the body. In the blood, β -alanine exists as a free amino acid, with plasma concentrations peaking within 30–60 minutes after ingestion and typically returning to baseline within 2 to 3 hours (26). A small fraction of β -alanine is metabolized by the liver via transamination to malonate semialdehyde, but the majority is taken up by peripheral tissues, especially skeletal muscle, where it serves as the rate-limiting substrate for carnosine synthesis (8). The efficiency of skeletal muscle uptake is influenced by transporter availability (e.g., PAT1 and TauT), substrate competition, and the saturable nature of these transporters. Thus, plasma β -alanine pharmacokinetics underscore the rationale for repeated or divided dosing strategies to maximize skeletal muscle carnosine accumulation while minimizing transient side effects.

Transport into Skeletal Muscle

The uptake of β -alanine into the skeletal muscle fibers is a tightly regulated, carrier-mediated process with TauT (32) serving as a primary route for β -alanine entry. Muscle TauT is strongly dependent on sodium (Na^+) and chloride (Cl^-) gradients, allowing β -alanine to accumulate against substantial concentration differences. Because intracellular β -alanine availability is the rate-limiting factor for carnosine synthesis, efficient transporter-mediated uptake directly determines how much carnosine can be produced in the muscle fibers (7,9). Transporter

density varies between fiber types, with Type II (fast-twitch) fibers typically achieving greater carnosine loading than Type I fibers due to higher β -alanine uptake and carnosine synthetase activity (26,35). Thus, β -alanine transport efficiency is a central determinant of muscle carnosine content and the effectiveness of supplementation strategies.

Regulation of Intracellular Carnosine Synthesis

Once inside the muscle fiber, β -alanine combines with L-histidine to form carnosine via the ATP-dependent enzyme carnosine synthase (CARNS1/ATPGD1) (9,19):



Intracellular L-histidine concentrations are generally much higher than those of β -alanine, making β -alanine the rate-limiting substrate for carnosine synthesis (26). Consequently, elevating sarcoplasmic β -alanine through supplementation directly enhances carnosine production. Long-term supplementation studies indicate that skeletal muscle can continuously accumulate carnosine over time, without reaching a strict upper limit, reflecting the efficiency and robustness of this transport and synthesis pathway (50). Given that muscle carnosine accumulation ultimately depends on the availability of circulating β -alanine, understanding the plasma kinetics of orally ingested β -alanine is essential for optimizing supplementation strategies.

PLASMA KINETICS OF TRADITIONAL β -ALANINE SUPPLEMENTATION

The efficacy of β -alanine (BA) as an ergogenic aid is linked to its pharmacokinetic profile following oral ingestion (52). While the ultimate objective of supplementation is to augment intramuscular carnosine stores, the rate and magnitude of this loading are dictated by the transient rise of BA in the systemic circulation. Recent evidence suggests that the significant variation observed in carnosine loading and subsequent ergogenic responses can be partially explained by the distinct pharmacokinetic profiles of individual users. Previous research by Blancquaert et al. (8) and Stautemas et al. (52) underscores that the variations in plasma kinetics are a primary reason why some individuals respond more robustly to supplementation than others. This variability suggests a potential need for personalized dosing strategies to induce a more homogenous pharmacokinetic and ergogenic response across diverse populations.

Upon ingestion, BA is characterized by rapid absorption through the gastrointestinal tract, which leads to a quick appearance in the blood plasma (58). Traditionally, peak plasma concentrations ($C_{\max}$) are reached within 30 to 60 minutes, followed by a rapid clearance from the system. BA possesses a relatively short half-life, typically estimated at approximately 25 minutes, which necessitates strategic dosing to maintain systemic levels conducive to muscle uptake (26). Stautemas et al. (52) investigated which dosing strategies (fixed versus weight-relative) evoke the most consistent plasma response and found significant inter-individual differences in the incremental area under the curve (iAUC). The iAUC was found to be non-linearly related to the dose, meaning that a simple change in dosage will not induce a predictable, linear effect on systemic exposure. The study concluded that neither fixed nor weight-relative dosing is entirely adequate, as variation remains high and is only partially correlated with anthropometric characteristics. This creates a clinical challenge where low

ingestion may be insufficient to affect performance, while high doses may trigger acute side effects.

The most prominent limitation to high-dose BA supplementation is the onset of paresthesia, a sensory side effect characterized by skin itching and tingling (16,18). While BA is primarily sought for its role in skeletal muscle, it is also distributed within the nervous system and skin tissues. These sensations typically manifest shortly after the plasma BA concentration begins to rise and persist for approximately 60 minutes, a timeframe that directly mirrors the rate of increase in plasma BA (47). The skin sensations evoked by BA ingestion are mediated by the Mas-related G-protein-coupled membrane D (MrgprD) expressed in cutaneous sensory neurons (40). These specific neurons innervate the skin and do not excite or modulate skeletal muscle fibers, which means the sensation is purely sensory and not indicative of muscular distress.

The severity of these symptoms is dose-dependent and tied to specific threshold concentrations. Early investigations by Harris et al. (26) and Décombaz et al. (16) established that acute doses of 400 to 500 mg are generally symptom-free. However, as the dose increases to 800 mg, mild symptoms such as flushing may occur. At a dose of 1.6 g, symptoms become significant for many participants, and by the time a single dose reaches 3.2 g, the apparent plasma threshold is crossed, often resulting in sensations described as "unpleasant." To mitigate these effects while still achieving carnosine loading, early protocols often split doses into 0.8 g increments taken throughout the day (16). Alternatively, the development of slow-release tablets has proven effective in slowing the rate of appearance in the blood and lowering the C_{max} without triggering paresthesia. The absence of side effects with slow-release formulations is directly associated with a blunted and extended time course of BA that allows for effective loading without the discomfort of traditional rapid-release supplements.

Overall, the plasma kinetics of BA ingestion represent a balance between maximizing systemic exposure for muscle carnosine synthesis and minimizing the transient rise in concentration that triggers paresthesia. Because the relationship between dose and systemic exposure is non-linear and highly variable between individuals, standardized dosing protocols often fall short of providing a uniform ergogenic response. The shift from traditional rapid-release supplements to split-dosing or slow-release formulations highlights a critical evolution in supplementation strategy. By blunting the peak plasma concentration and extending the time course of absorption, these methods bypass the threshold for MrgprD-mediated sensory side effects that ultimately allow for the higher cumulative doses necessary to optimize athletic performance.

ADVANCES IN β -ALANINE DELIVERY SYSTEMS

Research on β -alanine supplementation has expanded beyond performance outcomes to include advances in delivery technologies designed to optimize pharmacokinetic profiles, improve tolerability, and enhance dosing efficiency. Conventional β -alanine supplements are typically administered as immediate-release powders or capsules that produce rapid increases in plasma β -alanine concentrations following ingestion (44). Although these formulations effectively increase skeletal muscle carnosine concentrations, the rapid rise in circulating β -alanine can induce a transient tingling sensation (paresthesia), which is believed to result from the activation of cutaneous sensory neurons at elevated plasma concentrations (40).

To address these limitations, several formulation strategies have been developed to regulate β -alanine absorption kinetics. These include sustained-release tablets, modified-release capsules and powders, and emerging encapsulation technologies designed to control nutrient release while maintaining sufficient systemic exposure for muscle carnosine synthesis (15,41,60).

Sustained-Release Formulations

Sustained-release β -alanine formulations have been developed to address the rapid increases in plasma concentration associated with conventional immediate-release supplementation. These formulations typically use specialized tablet matrices or coated microgranules to regulate gastrointestinal dissolution and intestinal absorption that result in a more gradual rise in plasma β -alanine concentrations.

Controlled Absorption Profiles

Pharmacokinetic investigations demonstrate that sustained-release formulation substantially alters β -alanine absorption kinetics. In an early controlled study, slow-release β -alanine tablets delayed the time to peak plasma concentration (T_{max}) while maintaining comparable systemic exposure, measured as the area under the curve (AUC) relative to β -alanine administered in solution (16).

Subsequent work evaluating a sustained-release tablet containing a controlled-release powder blend reported significantly greater systemic exposure, with approximately a 2.1-fold increase in AUC compared with a conventional tablet formulation (15). More recently, a randomized controlled trial assessing a sustained-release β -alanine microgranule formulation administered at $15 \text{ g} \cdot \text{day}^{-1}$ for 30 days reported good tolerability and minimal sensory symptoms in recreationally trained men (41). Collectively, these findings demonstrate that formulation design can meaningfully influence β -alanine pharmacokinetics and tolerability.

Reduced Peak Plasma Concentrations

A key advantage of sustained-release β -alanine formulations is the attenuation of peak plasma concentrations (C_{max}). Pharmacokinetic comparisons indicate that the slow-release tablets produce substantially lower C_{max} than the immediate-release formulations despite equivalent dosing (16). Similarly, a controlled-release powder formulation produced a 1.6-fold higher C_{max} compared with a sustained-release tablet, illustrating the influence of formulation design on peak systemic exposure (15).

These differences are physiologically relevant because paresthesia associated with β -alanine ingestion is believed to occur when circulating β -alanine activates Mas-related G-protein-coupled receptors (MrgprD) located on cutaneous sensory neurons (40). By reducing C_{max} levels while maintaining total systemic exposure, sustained-release formulations may limit receptor activation and thereby reduce the sensory symptoms associated with β -alanine supplementation.

Evidence for Improved Tolerability

Improved tolerability represents a primary objective of sustained-release β -alanine formulations. In a study that administered $1.6 \text{ g} \cdot \text{day}^{-1}$ of slow-release β -alanine tablets for 7 weeks, the participants reported significantly lower paresthesia compared with immediate-release supplementation (16).

Similarly, a randomized controlled trial evaluating a sustained-release β -alanine microgranule formulation administered at $15 \text{ g} \cdot \text{day}^{-1}$ for 30 days reported good overall tolerability, minimal sensory symptoms, and no clinically relevant changes in hematological or biochemical safety markers (41). Together, these findings indicate that sustained-release formulations can reduce C_{max} and improve tolerability without compromising systemic exposure.

Modified-Release Capsules and Tablets

Modified-release capsules and tablets represent another strategy for optimizing β -alanine pharmacokinetics. Unlike conventional immediate-release formulations, these delivery systems employ polymer matrices, coated capsules, or specialized powder blends to regulate dissolution rates and modulate intestinal absorption. The goal is to maintain sustained plasma β -alanine concentrations while minimizing rapid increases that may trigger sensory side effects (15,41,61).

Pharmacokinetic Comparisons

Pharmacokinetic comparisons between the modified-release and the conventional β -alanine formulations demonstrate clear differences in plasma concentration profiles. Investigations comparing sustained-release and rapid-release β -alanine supplementation report comparable increases in skeletal muscle carnosine despite the differences in absorption kinetics that suggest slower absorption rates do not impair the physiological effectiveness of β -alanine (61).

More recently, a crossover pharmacokinetic study evaluating a controlled-release β -alanine powder reported significantly greater systemic exposure than a sustained-release tablet. Participants receiving the controlled-release powder exhibited prolonged elevations in plasma β -alanine concentrations and greater overall bioavailability relative to the reference formulation (15). These findings highlight the importance of formulation design in determining the efficiency of β -alanine delivery.

Effects on Dosing Strategies

Modified-release delivery systems may also influence practical dosing strategies used during β -alanine supplementation. Traditional β -alanine supplementation protocols often recommend dividing daily intake into multiple small doses (approximately 0.8 to 1.6 g per dose) to minimize paresthesia and maintain circulating β -alanine concentration throughout the day (44,58). Although effective, such protocols may require frequent dosing and could reduce adherence during the extended supplementation periods necessary to substantially increase skeletal muscle carnosine concentrations.

Modified-release formulations may allow larger single doses or fewer daily administrations while maintaining acceptable tolerability. By slowing gastrointestinal dissolution and attenuating peak plasma concentrations, these delivery systems may reduce the likelihood of paresthesia while sustaining circulating β -alanine availability for longer periods. Consequently, modified-release technologies may simplify supplementation protocols and improve adherence during chronic supplementation strategies aimed at maximizing skeletal muscle carnosine concentrations (50,51). Recent systematic evidence further emphasizes the importance of formulation and dosing strategies in optimizing β -alanine supplementation protocols for both performance outcomes and practical implementation in athletic populations (44).

Novel Encapsulation Technologies

Encapsulation technologies have emerged as a promising approach for improving the delivery characteristics of nutraceutical compounds, including amino acid supplements such as β -alanine. Encapsulation involves incorporating bioactive compounds within protective matrices that regulate nutrient release following ingestion. These systems act as diffusion barriers that slow gastrointestinal dissolution and allow gradual release of the encapsulated compound, thereby modifying absorption kinetics and potentially improving stability during digestion (54).

Microencapsulation

Microencapsulation technologies are widely used in functional foods and dietary supplements to improve stability, regulate release kinetics, and enhance bioaccessibility of bioactive compounds (13). Although the research that specifically examines microencapsulated β -alanine remains limited, these systems may attenuate rapid increases in plasma β -alanine concentrations that occur following ingestion of conventional immediate-release formulations.

Recent pharmacokinetic research reported markedly enhanced systemic exposure with an encapsulated β -alanine formulation, demonstrating approximately 4.5-fold greater circulating β -alanine concentrations compared with the conventional formulations (23). While these findings require replication, they suggest that encapsulation strategies may substantially alter β -alanine pharmacokinetics.

Lipid-Based Delivery

Lipid-based delivery systems represent another emerging strategy for improving the oral bioavailability of nutraceutical compounds. These technologies incorporate bioactive ingredients into lipid carriers, such as liposomes, nanoemulsions, or lipid nanoparticles to enhance gastrointestinal transport and facilitate absorption via lipid pathways (45).

A recent randomized study investigating a hydro-oleo lipid-encapsulated β -alanine complex (commercially developed as TriBsyn™) reported a substantially higher β -alanine concentration compared with conventional ingestion, with approximately 4.5-fold greater plasma β -alanine concentration following supplementation (23). These results suggest that lipid-based delivery technologies may enhance the systemic availability of β -alanine and improve delivery efficiency compared with traditional formulations. Notably, the increased systemic exposure (AUC and Cmax) reported was not accompanied by a corresponding increase in paresthesia intensity, with sensory symptoms in fact being lower than those observed with the conventional reference formulation (23). This decoupling of plasma kinetic parameters from sensory response is mechanistically intriguing because the prevailing model attributes paresthesia primarily to the rate and magnitude of plasma β -alanine elevation acting at cutaneous MrgprD (16,26,40,52). Possible contributing factors include modulated dissolution and dispersion behavior of the encapsulated complex, particle-size effects on the rate of intestinal absorption, and altered gastric emptying kinetics; the relative contribution of each, however, remains to be characterized in larger replication studies. Importantly, these observations derive from a single acute-dose pharmacokinetic study ($n = 12$) in older adults under fasting conditions, and the relationship between formulation-driven increases in AUC and longer-term skeletal muscle carnosine accumulation has not yet been directly evaluated. Nevertheless, the finding suggests that encapsulation-based formulations may achieve favorable systemic exposure through a kinetic profile that is mechanistically distinct from that produced by conventional sustained-release approaches.

Potential Improvements in Bioavailability

Encapsulation technologies may offer several advantages for β -alanine supplementation, including improved bioavailability, enhanced formulation stability, and more controlled nutrient release. By regulating gastrointestinal absorption kinetics, microencapsulation and lipid-based delivery systems may modulate the relationship between systemic exposure and sensory response, with at least one study reporting attenuated paresthesia despite enhanced plasma β -alanine availability (23). The mechanistic basis for this dissociation between plasma kinetics and sensory activation remains to be fully characterized.

Although the application of these technologies within sports nutrition remains relatively recent, advances in nutraceutical formulation science suggest that encapsulated delivery systems may represent a next-generation approach for optimizing β -alanine supplementation protocols. Future research is needed to determine whether these technologies enhance the efficiency of skeletal muscle carnosine loading or improve the tolerability of supplementation in athletic populations.

STRATEGIES TO REDUCE PARESTHESIA

Paresthesia is the most consistently reported and most extensively studied adverse sensation associated with β -alanine (BA) supplementation. The phenomenon is characterized by transient itching, tingling, or flushing typically localized to the face, neck, scalp, and upper extremities, beginning shortly after ingestion of a sufficient dose and resolving within approximately 60 to 90 minutes (16,18,47). Mechanistically, paresthesia is mediated by activation of MrgprD on cutaneous primary sensory neurons by circulating BA; activation of these receptors produces histamine-independent itch and tingling that does not reflect any pathological process within skeletal muscle (40). The intensity of these symptoms is dose-dependent and tightly linked to peak plasma concentration (C_{max}), with a single dose of approximately 800 mg representing a practical threshold above which symptoms become noticeable in many individuals, and doses of 1.6 g and above frequently producing pronounced sensations (16,26). Although paresthesia is benign and self-limiting, it is the most commonly cited reason for non-adherence to supplementation protocols and represents a meaningful obstacle to the sustained, multi-week dosing required to elevate skeletal muscle carnosine (18,44,47). Strategies to mitigate paresthesia therefore aim to attenuate C_{max} while preserving total systemic exposure (AUC), and they fall broadly into 4 categories: (a) dose splitting; (b) sustained-release formulations; (c) co-ingestion strategies; and (d) emerging encapsulation and lipid-based delivery systems.

Dose Splitting

Dose splitting was the first and remains the most widely used strategy for managing BA-induced paresthesia. The approach divides total daily intake (typically 4 to 6 g·day⁻¹) into multiple smaller doses of approximately 0.8 to 1.6 g, ingested at intervals of 2 or more hours throughout the day (26,44,58). The pharmacokinetic rationale is straightforward because paresthesia severity tracks C_{max} rather than AUC, fractionating the daily dose suppresses each individual peak below the MrgprD activation threshold while still delivering the cumulative substrate required for progressive carnosine loading. Early controlled investigations established that single 0.8 g doses are typically symptom-free; whereas, single doses of 1.6 g produce noticeable paresthesia and 3.2 g produces sensations frequently described as unpleasant (16,26). When 6 g·day⁻¹ is administered as 4 to 8 smaller doses spread across the

day, paresthesia is generally well tolerated and adherence is maintained over multi-week loading phases (50,58).

Despite its proven efficacy, dose splitting carries practical drawbacks. Multiple daily administrations impose a behavioral burden over the 4 to 10 weeks typically required to achieve substantial muscle carnosine elevation, and missed doses are more likely under regimens requiring 4 or more daily administrations (44). Additionally, although divided dosing minimizes paresthesia, it does not necessarily produce the most efficient carnosine loading per unit of daily intake, since sustained, lower-amplitude plasma elevations may be more conducive to transporter-mediated uptake than discrete, brief peaks (47,52). These considerations have motivated continued development of formulation-based alternatives that achieve favorable plasma kinetics with fewer administrations per day.

Sustained-Release Supplementation

Sustained-release and modified-release formulations represent the principal pharmaceutical alternative to behavioral dose splitting. As described in *Advances in β -Alanine Delivery Systems*, these technologies (including matrix tablets, coated microgranules, controlled-release powders, and emerging encapsulation systems) slow gastrointestinal dissolution and intestinal absorption, producing a flatter and more prolonged plasma BA profile (15,16,41). The pharmacokinetic effect on tolerability is well established: in a 7-week controlled trial, slow-release BA tablets administered at $1.6 \text{ g} \cdot \text{day}^{-1}$ produced significantly less paresthesia than immediate-release formulations at equivalent doses (16), and a 30-day randomized trial of a sustained-release microgranule administered at $15 \text{ g} \cdot \text{day}^{-1}$ (a dose far exceeding any tolerated as an immediate-release bolus) reported good overall tolerability with minimal sensory symptoms (41). The slow-release tablet platform evaluated in Décombaz et al. (16) and Varanoske et al. (61), commercially available as SR CarnoSyn®, represents the longest-standing and most extensively characterized sustained-release β -alanine dataset to date.

The clinical implication is that sustained-release formulations may permit larger single doses and fewer administrations per day while maintaining or improving the consistency of muscle carnosine loading (15,41). This benefit is mechanistically aligned with the saturable, transporter-mediated uptake described in *Mechanisms of β -Alanine Absorption and Transport*: by holding plasma BA within a moderate, sustained range, these formulations may make more efficient use of PAT1- and TauT-mediated transport into skeletal muscle, particularly in light of the non-linear dose–exposure relationship that limits the utility of large acute boluses (52). Outstanding questions include whether long-term carnosine accumulation with sustained-release dosing differs quantitatively from that achieved with conventional split dosing in well-controlled head-to-head trials, and how formulation properties interact with inter-individual differences in gastrointestinal transit and transporter expression.

Co-Ingestion Strategies

Food Matrix Effects

Co-ingestion of BA with food represents a simple, accessible strategy that may attenuate C_{max} through delayed gastric emptying and slower intestinal transit. Although direct mechanistic studies of food-induced modulation of BA kinetics are limited, broader pharmacokinetic principles indicate that the presence of a mixed meal, particularly one containing fat and protein, generally extends T_{max} and lowers C_{max} for orally administered amino acids and small water-soluble compounds (23,26). Sports nutrition position statements explicitly recommend ingestion of BA with meals as a practical means of reducing paresthesia (44,58),

and this approach is compatible with both immediate-release and sustained-release formulations. The food matrix may also confer secondary benefits, including improved adherence through anchoring of supplement intake to existing eating patterns. Importantly, food-induced attenuation of C_{max} has not been associated with reduced muscle carnosine loading, consistent with the broader observation that AUC, rather than C_{max}, is the relevant determinant of intramuscular accumulation over weeks of supplementation (47,52).

Amino Acid Competition

Because BA shares transport systems with several other small amino acids, co-ingestion with competitive substrates has been examined as a potential modulator of absorption. PAT1 transports glycine, L-proline, and L-alanine in addition to BA (3,4,57), and TauT recognizes BA, taurine, and other β -amino acids (19,56). Theoretically, co-ingestion of competitive substrates could slow BA absorption and attenuate C_{max}. However, the evidence of clinically meaningful interaction at typical supplemental doses is limited, and at standard 3 to 6 g·day⁻¹ regimens, BA does not appear to produce sustained taurine depletion in human skeletal muscle, although competitive interactions are observable in animal models (26,32). The reverse concern that co-ingestion of taurine or other PAT1 substrates might reduce BA bioavailability is similarly not supported by current evidence at supplemental doses, but remains an area for further investigation, particularly in formulation contexts where multiple amino acids are combined in pre-workout matrices.

Emerging Encapsulation and Lipid-Based Delivery

Encapsulation and lipid-based delivery technologies (described mechanistically in Novel Encapsulation Technologies) have recently been investigated as a distinct approach to managing β -alanine tolerability. Whereas sustained-release formulations attenuate paresthesia primarily by lowering C_{max}, emerging encapsulation strategies have produced pharmacokinetic profiles that depart from this paradigm. In a randomized crossover study in older adults, a hydro-oleo lipid-encapsulated β -alanine complex (commercially developed as TriBsyn™) produced approximately 4.5-fold greater AUC and substantially higher C_{max} than conventional β -alanine, yet was associated with reduced paresthesia intensity (23). This decoupling of C_{max} and sensory response is mechanistically intriguing because the prevailing model attributes paresthesia severity primarily to the rate and magnitude of plasma β -alanine elevation acting at cutaneous MrgprD (16,26,40,52). Possible contributing factors include altered dissolution and dispersion behavior of the engineered complex, particle-size effects on the rate of intestinal absorption, and modulated gastric emptying kinetics, although the relative contribution of each remains to be characterized. The available evidence comes from a single acute-dose pharmacokinetic study (n = 12) under fasting conditions and did not include longitudinal skeletal muscle carnosine endpoints; replication in larger and more diverse cohorts, with chronic dosing and direct measurement of muscle carnosine accumulation, will be necessary before encapsulation-based delivery can be positioned alongside sustained-release as an established paresthesia-mitigation strategy. Even with these caveats, the observation that systemic exposure can be enhanced without a corresponding increase in sensory symptoms suggests that this class of formulations represents a meaningfully different design space from traditional sustained-release approaches and warrants further mechanistic and clinical investigation.

Implications for Adherence and Long-Term Supplementation

The long supplementation period of 4 to 10 weeks required for substantial muscle carnosine elevation, with continued accumulation observable through at least 24 weeks (50) make

adherence a primary determinant of supplementation effectiveness in real-world settings. Paresthesia is consistently identified as the most common reason for discontinuation, and meta-analytic evidence supports a favorable overall safety profile for BA supplementation across diverse populations, with paresthesia identified as the only side effect of practical significance (18). The strategies described above (dose splitting, sustained-release formulations, co-ingestion with food, and emerging encapsulation and lipid-based delivery systems) operate through distinct mechanisms. Dose splitting, sustained-release, and co-ingestion strategies converge on a common pharmacokinetic objective of lowering C_{max} sufficiently to remain below the MrgprD activation threshold while sustaining systemic BA exposure adequate for transporter-mediated muscle uptake; encapsulation-based approaches, by contrast, have produced preliminary evidence of attenuated paresthesia even in the context of elevated C_{max} (23), suggesting a mechanism that is not yet fully characterized. From an applied perspective, the choice among these strategies is increasingly a question of practicality rather than efficacy. Sustained-release formulations, and in particular the SR CarnoSyn® tablet platform that supports the most extensive long-term sustained-release dataset (16,61), offer a compelling combination of pharmacokinetic optimization and reduced dosing frequency, which may be particularly relevant for athletes balancing multiple supplementation regimens and for older adults or clinical populations in whom adherence to multi-dose-per-day protocols is challenging (21,41,43). The continued development of formulation technologies that further flatten the plasma BA profile together with personalized dosing approaches informed by inter-individual differences in pharmacokinetics (52) are likely to define the next generation of BA supplementation protocols.

IMPLICATIONS FOR PERFORMANCE AND CLINICAL APPLICATIONS

The translation of BA pharmacokinetics and muscle carnosine loading into functional outcomes spans a continuum from athletic performance to clinical and aging-related applications. Although the bulk of the existing literature has examined ergogenic effects in young, trained populations, growing interest in carnosine biology has extended investigation into older adults, clinical cohorts, and populations characterized by metabolic dysregulation (37,39,46,63). The advances in delivery systems described in *Advances in β-Alanine Delivery Systems* have direct implications for each of these contexts because they reshape the trade-off between dose, exposure, tolerability, and adherence.

Athletic Performance

High-Intensity Exercise

The most robust performance benefits of BA supplementation occur in tasks in which intracellular acidosis is a substantial contributor to fatigue. Meta-analyses consistently report small but significant improvements in exercise capacity and performance during continuous and intermittent activities lasting approximately 30 seconds to 10 minutes, which is the duration window over which glycolytic flux and H⁺ accumulation reach their greatest functional impact (22,29,49,51). The mechanistic basis is well established: elevated muscle carnosine, achieved through sustained BA supplementation, augments non-bicarbonate intracellular buffering capacity, thereby attenuating the decline in intracellular pH during high-intensity work and delaying the impairment of cross-bridge cycling, Ca²⁺ handling, and glycolytic enzyme function (17,20,37). Effect sizes are modest in absolute terms but practically meaningful in competitive contexts where small margins separate performance outcomes (22,51). The relationship between supplementation, muscle carnosine accumulation, and ergogenic outcomes is broadly dose-dependent across the typical supplemental range. Higher daily β-alanine intake within the

conventional 3 to 6 g·day⁻¹ window yields larger absolute increases in muscle carnosine over the loading period (48,50), and Bayesian individual-data modelling indicates a near-monotonic relationship between cumulative β -alanine dose and the magnitude of carnosine response across diverse populations (48). Achieved muscle carnosine concentration, in turn, correlates with the magnitude of buffering-related performance improvement, although individual studies vary in their power to detect this gradient and a strict linear dose-response at the performance level is not always observed (29,50,51). A recent systematic review of dosing strategies in strength and power contexts further supports dose as a critical determinant of ergogenic magnitude, with cumulative dose and consistency of administration emerging as key moderators (44). These dose-response relationships have direct implications for delivery-system selection: any formulation strategy that improves real-world adherence to a target daily intake, by reducing paresthesia or dosing frequency, is likely to translate into more consistent muscle carnosine loading at the population level even in the absence of a difference in single-dose pharmacokinetics.

From a delivery-system perspective, modified-release and sustained-release formulations are particularly relevant for athletic populations who must adhere to BA loading protocols across weeks to months of training. By reducing the number of daily administrations required to achieve a given total daily intake without inducing paresthesia, these formulations may improve adherence and, in turn, the consistency of muscle carnosine loading at the population level (41,44). Whether these formulations alter performance outcomes relative to optimally adherent split-dose protocols is an open question. Current evidence suggests that performance benefits scale with achieved muscle carnosine concentration rather than with the specific delivery format used to attain it (50,61).

Repeated Sprint Performance

Repeated sprint activities such as football, basketball, hockey, and soccer, represent a setting in which BA-mediated buffering may be especially valuable. The repeated short-duration, high-intensity efforts that define these activities produce cumulative intracellular acidosis between bouts, and the rate of pH recovery during incomplete rest periods is a key determinant of subsequent performance. Although the heterogeneity of repeated sprint protocols complicates direct meta-analytic synthesis, several individual studies and reviews report improvements in repeated-sprint and intermittent high-intensity performance following BA supplementation (29,44,49,51). Recent systematic evidence further supports the role of BA in strength- and power-oriented contexts, with dosing strategies emerging as a key moderator of the magnitude of benefit (44). For athletes engaging in repeated sprint disciplines, the practical advantages of sustained-release formulations, including reduced dosing burden and minimized paresthesia during precompetition periods, are particularly salient (41,44).

Aging Populations

Muscle Buffering Capacity

Muscle carnosine concentrations decline with aging, contributing to reductions in intracellular buffering capacity and potentially to the broader functional decrements observed in older adults (37). Because BA availability remains the rate-limiting determinant of carnosine synthesis irrespective of age, supplementation represents a plausible strategy for restoring or augmenting muscle carnosine in the aging populations. Controlled trials in older adults have demonstrated that BA supplementation can elevate muscle carnosine concentrations and enhance markers of physical performance and working capacity (21,43).

Functional Performance

Beyond muscle biochemistry, BA supplementation has been associated with improvements in functional capacity in older and middle-aged individuals, including measures of physical working capacity, endurance, and post-exercise executive function (21,43). These findings are consistent with carnosine's broader physiological roles, including antioxidant and anti-glycation activities, which may be particularly relevant in aging tissues exposed to chronic low-grade oxidative stress and accumulated glycoxidative damage (14,28,59,63). Adherence considerations are especially important in older populations, where polypharmacy and complex daily routines may make multi-dose-per-day regimens impractical. Sustained-release formulations that permit fewer daily administrations represent a potentially important advance for translational application of BA supplementation in aging populations (41).

Potential Therapeutic Areas

Neuromuscular Disorders

Carnosine's combination of buffering, antioxidant, anti-glycation, and Ca^{2+} -modulatory activities has stimulated interest in its therapeutic potential for neuromuscular and neurological conditions characterized by oxidative stress, mitochondrial dysfunction, and contractile impairment. Preclinical and clinical evidence suggests neuroprotective effects of carnosine in models of stroke and broader brain pathology (6,34), and comprehensive reviews have outlined a range of potential clinical applications based on its pleiotropic biochemical actions (37). Although translation from preclinical models to definitive clinical applications in neuromuscular disease remains preliminary, the ability of oral BA supplementation to elevate carnosine in skeletal muscle, and potentially in other excitable tissues, provides a feasible delivery route for future therapeutic investigation.

Metabolic Health

Carnosine's anti-glycation and antioxidant activities have prompted investigation of BA and carnosine supplementation in the context of metabolic disorders, particularly type 2 diabetes and prediabetes. Randomized clinical trials and systematic reviews report that carnosine supplementation can produce favorable changes in fasting glucose, HbA1c, advanced glycation end products, and inflammatory markers in patients with type 2 diabetes (33,39,46). Mechanistically, these effects are consistent with carnosine's ability to scavenge reactive carbonyl species, inhibit AGE formation, and modulate insulin sensitivity (5,14). Although effect sizes are modest and additional well-controlled trials are warranted, the available evidence supports the position that BA and carnosine supplementation may have metabolic benefits that extend beyond exercise performance. Sustained-release and encapsulated delivery systems that improve adherence and bioavailability may be particularly relevant in clinical populations, where chronic supplementation across months or years is the norm rather than the exception (15,23,41).

FUTURE RESEARCH DIRECTIONS

Despite three decades of research establishing the efficacy and safety of BA supplementation, several questions remain that are particularly relevant given recent advances in delivery technologies. Future research should prioritize the following areas.

Comparative Pharmacokinetic Studies

Although individual studies have characterized the plasma kinetics of immediate-release, sustained-release, modified-release, and lipid-encapsulated BA formulations, direct head-to-

head comparisons under standardized conditions remain relatively limited (15,16,23). Crossover designs that compare multiple delivery formats within the same individuals, controlling for inter-individual pharmacokinetic variability identified in recent work (52), would clarify the relative magnitude of differences in C_{max}, T_{max}, AUC, and tolerability across formulations. Such studies should also include longitudinal endpoints (i.e., changes in muscle carnosine over weeks of supplementation) to determine whether differences in single-dose pharmacokinetics translate into differences in long-term loading efficiency. Standardization of pharmacokinetic protocols, including timing of blood sampling, fasting versus fed state, and analytical methods, would improve comparability across studies.

Long-Term Safety and Adherence

Existing meta-analytic safety evidence supports a favorable risk profile for BA supplementation, with paresthesia identified as the only side effect of practical relevance and no meaningful concerns documented at typical supplemental doses (18). However, the duration of follow-up in most existing trials rarely exceeds 12 weeks, and longer-term safety data, particularly in clinical populations and older adults using BA chronically for metabolic or aging-related indications, would strengthen the evidence base for sustained use. Adherence is similarly under-studied as a discrete outcome, despite being a primary determinant of effectiveness. Future trials comparing delivery formats should include validated adherence measures and explicitly evaluate whether sustained-release formulations translate reduced paresthesia into improved real-world compliance (41,44).

Personalized Dosing Strategies

Substantial inter-individual variability in muscle carnosine response to BA supplementation has been documented, with some individuals showing markedly larger increases than others under identical protocols (47,48,52). Stautemas et al. (52) demonstrated that fixed and weight-relative dosing each produce non-linear, only partially predictable plasma exposure profiles, and that variability is incompletely explained by anthropometric characteristics. These observations argue for the development of personalized dosing strategies informed by factors that may include baseline muscle carnosine, fiber-type composition, training status, transporter genotype (e.g., SLC36A1, SLC6A6), gastrointestinal transit characteristics, and gut microbiome composition (4,7,35). Integration of pharmacokinetic modeling with delivery-system design represents a promising direction for translating mechanistic insights into clinically actionable protocols.

Integration with Other Ergogenic Nutrients

BA is increasingly co-administered with other ergogenic and recovery-oriented nutrients (including sodium bicarbonate, creatine, caffeine, and various amino acids) in commercial supplement formulations and applied athletic settings. Because carnosine's intracellular buffering action is mechanistically complementary to extracellular buffering provided by sodium bicarbonate, theoretical synergies have motivated combined supplementation studies with mixed but generally supportive results (38). However, formulation-level interactions, including potential transporter-level competition between BA and other amino acids in pre-workout matrices (4,56) and pharmacokinetic interactions in lipid-encapsulated co-formulations (23,45), have received limited systematic investigation. Future research should examine both the additive performance benefits and the pharmacokinetic interactions of co-formulated products, with attention to whether sustained-release and encapsulation technologies can be applied to multi-ingredient formulations without compromising the kinetic profile of BA itself.

CONCLUSIONS

β -alanine supplementation produces reliable, dose-dependent elevations in skeletal muscle carnosine and small but consistent improvements in high-intensity exercise performance, supported by a coherent mechanistic framework that links substrate availability, transporter-mediated uptake, intracellular dipeptide synthesis, and downstream physiological functions including pH buffering, antioxidant defense, anti-glycation activity, and modulation of contractile function. The principal limitation of conventional immediate-release supplementation is not efficacy but tolerability and adherence: the rapid plasma kinetics that produce paresthesia constrain acute dosing and necessitate frequent split dosing across the multi-week loading periods required for substantial muscle carnosine accumulation.

Recent advances in delivery technologies, including sustained-release tablets, modified-release capsules and powders, microencapsulation, and lipid-based delivery systems, directly address this limitation by attenuating peak plasma concentrations while preserving or enhancing total systemic exposure. The available pharmacokinetic and tolerability evidence indicates that these formulations can permit larger single doses and fewer daily administrations without producing the paresthesia that limits conventional supplementation, with the prospect of improved adherence over chronic supplementation periods. From a mechanistic standpoint, the flatter plasma BA profiles produced by these formulations are well aligned with the saturable, transporter-mediated nature of skeletal muscle uptake and may make more efficient use of available transport capacity than acute boluses.

Translating these advances into optimized supplementation protocols will require direct head-to-head pharmacokinetic comparisons, longer-term efficacy and safety studies, and the development of personalized dosing strategies that account for the substantial inter-individual variability observed in plasma kinetics and muscle carnosine response. The expanding clinical interest in carnosine for aging, metabolic, and neuromuscular applications further increases the importance of delivery technologies that support sustained, well-tolerated supplementation outside of athletic contexts. Together, these developments mark a transition in BA supplementation science from a focus on whether and how much to a focus on how best to deliver, a shift that promises to enhance both the efficacy and the practical applicability of one of the most thoroughly studied ergogenic supplements in sports nutrition.

DATA AVAILABILITY STATEMENT

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

CONFLICTS OF INTEREST

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Mechanism for Driving the National Strategy on Sports Promotion for Excellence of the National Sports University into Practice

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ABSTRACT

Chudam W, Sukdee N. Mechanism for Driving the National Strategy on Sports Promotion for Excellence of the National Sports University into Practice. The purpose of this research was: (a) to study the mechanisms for implementing the national strategy for promoting sports excellence by the Thailand National Sports University; (b) to develop mechanisms for implementing the national strategy for promoting sports excellence by the Thailand National Sports University; and (c) to evaluate the mechanisms for implementing the national strategy for promoting sports excellence by the Thailand National Sports University. The research employed the Delphi future research process, involving interviews with 5 experts and surveys with 17 specialists. Additionally, a Focus Group discussion was conducted with 11 selected experts to validate the suitability and feasibility of the mechanisms. The research instruments included semi-structured interviews and questionnaires. The data were analyzed using median, mode, and interquartile range statistics. The findings indicated that the mechanisms for implementing the national strategy for promoting sports excellence comprised **7 Aspects**: (a) Management; (b) Planning and Implementation; (c) Budget Management; (d) Personnel Management; (e) Awareness and Recognition; (f) Integration and Participation; and (g) Monitoring and Evaluation. A total of 58 components were identified, and all experts agreed with each component, showing consistent opinions across all the criteria. The Focus Group discussions confirmed the practical feasibility and appropriateness of these mechanisms, with some additional suggestions provided. There was a consensus that these mechanisms could be effectively implemented.

Delphi Future Research, National Strategy Implementation, Practical Application, Sports Excellence

INTRODUCTION

Thailand has established a long-term national development direction through the National Strategy (11), which articulates the vision of national security, prosperity, and sustainability, supported by strategic pillars that emphasize human resource development, enhanced competitiveness, and effective public sector management. It is within this framework that sports development is positioned as a relevant and measurable national agenda through associated master plans, particularly those that focus on sports potential and research and innovation, which highlight the role of sport science, personnel development, and innovation-based implementation as enabling conditions for achieving national goals (11). Such policy directions are further reinforced by national development planning that recognizes the importance of human capital and integrated implementation capacity, indicating that progress toward national objectives depends not only on well-defined strategies but also on coordinated execution and stakeholder alignment across systems and institutions (10).

Subsequently, Thailand's sports policy direction has been consolidated into a systematic implementation framework through the Seventh National Sports Development Plan (18) that adopts an upstream–midstream–downstream approach, and it defines 5 interconnected development areas spanning: (a) foundational sports; (b) mass sports participation; (c) excellence and professional sports; (d) sports personnel development; and (e) sports industry development (9). This progression of policy development demonstrates that Thailand's national agenda increasingly conceptualizes sports not as an isolated recreational activity, but as a strategic system linked to public health, human development, institutional capacity building, and national competitiveness.

Despite the presence of comprehensive strategic frameworks and structured national plans, a critical challenge remains in translating national priorities into consistent and measurable institutional-level outcomes. In practice, the implementation of sports excellence promotion requires mechanisms that can operationalize the policy objectives into concrete organizational processes, clarify roles and responsibilities, enable cross-unit coordination, and provide actionable pathways that connect planning to execution and evaluation. However, existing policy documents largely function as strategic frameworks and development directives, while the operational mechanisms required for effective institutional implementation, particularly those that are validated, context-specific, and feasible under real organizational constraints remain insufficiently articulated. This gap is important given that the success of the national development and sports plans ultimately depends on the ability of implementing organizations to sustain coordinated action, integrate multi-dimensional development components, and ensure continuity across stakeholders and functional domains (10). Therefore, the absence of an evidence-informed implementation mechanism constitutes a key systemic limitation that may reduce the effectiveness and sustainability of national efforts to drive sports promotion for excellence.

Within this national context, Thailand National Sports University represents a strategically relevant institutional influence because its mandates align directly with the human resource and capacity-building orientation of national strategy and sports development planning. As a specialized institution in sports education and training, the university has the potential to function as a central mechanism for strengthening sports personnel development, enhancing sport science application, and supporting the structured advancement of sports excellence pathways.

Consequently, developing an institutional mechanism for driving the national strategy on sports promotion for excellence within Thailand National Sports University is essential for strengthening policy-to-practice translation and for enabling systematic coordination across the multi-layered components of sports development from foundational preparation to elite performance outcomes. To ensure that such a mechanism is both credible and practically applicable, expert consensus is required because sports excellence promotion is inherently complex, multi-stakeholder, and dependent on specialized knowledge from diverse sectors. Accordingly, this study employed the Ethnographic Delphi Futures Research (EDFR) research technique, which is designed to gather expert opinions systematically and independently, reduce direct interpersonal influence, and refine collective agreement through iterative rounds of feedback, thereby producing reliable conclusions that can support decision-making and future-oriented implementation planning (13).

Hence, the purpose of this study was to develop and to validate a mechanism for driving the national strategy on sports promotion for excellence within Thailand National Sports University through an expert consensus process. Specifically, this study synthesized national strategic directions and sports development frameworks into an institutional implementation structure, identified and refined key mechanism components and operational guidelines that support coordinated execution, and evaluated the suitability and feasibility of the proposed mechanism for practical adoption. By generating a consensus-based and context-sensitive mechanism aligned with national strategy and Thailand's sports development planning, this study seeks to strengthen institutional implementation capacity and contribute to sustainable advancement of sports excellence within Thailand's national sports development system (9,11).

METHODS

This study employed a research and development design using the Delphi technique to develop and validate mechanisms for implementing the national strategy on sports excellence within the Thailand National Sports University. The research process consisted of 3 sequential phases: (a) preliminary document review and semi-structured interviews; (b) expert consensus development through multi-round Delphi surveys; and (c) validation of suitability and feasibility through focus group discussion. Both qualitative and quantitative data were used to ensure methodological triangulation and strengthen the credibility of the proposed mechanisms:

Procedure

The study was conducted after dividing it into 3 steps as follows:

Step 1 consisted of 2 Phases. Phase 1 required the carrying out of the preliminary data survey by analyzing and synthesizing the research documents and reports related to concepts, principles, and theories that were used to formulate a conceptual framework for the research study. Phase 2 used semi-structured interviews with experts and specialists.

Step 2 consisted of the mechanisms for driving the national sports excellence strategy of the Thailand National Sports University into practice by using questionnaires and related research as well as opinions from experts and those directly involved in the operations. The steps were as follows: (a) The researchers used preliminary data from Step 1 to create research tools according to the research conceptual framework, which included a 5-point rating scale

questionnaire. (b) Then, the questionnaire was sent to experts for the second round of responses and collected opinions on the mechanisms for driving the national sports excellence strategy of the Thailand National Sports University into practice. The data were analyzed statistically and then collected for the third round to achieve both practical and complete mechanisms for driving the national sports excellence strategy of the Thailand National Sports University into practice.

Step 3 consisted of the researchers presenting the mechanisms for driving the national sports excellence strategy of the Thailand National Sports University into practice that were created for the evaluation of suitability and feasibility according to the opinions of experts through focus group discussions.

Participants

The informant group included individuals involved in the mechanism for driving the national strategy for promoting sports excellence into practice at the Thailand National Sports University. The informants were categorized as follows:

1. The research Informant Group, selected by Purpose Sampling, consisted of 11 people. The Group studied the mechanism for driving the national strategy for promoting sports excellence at the Thailand National Sports University into practice to develop questions for the semi-structured interview. The Sample Group, selected by Purpose Sampling, included 5 people who were interviewed about the mechanism for driving the national strategy for promoting sports excellence at the Thailand National Sports University into practice.
2. To study the mechanism for driving the national strategy for promoting sports excellence at the Thailand National Sports University into practice, a questionnaire was used to gather opinions from experts and specialists, employing the Delphi technique. The Sample Group, selected by Purpose Sampling, consisted of 17 individuals.
3. The confirmation of the appropriateness and feasibility of the mechanism for driving the national strategy for promoting sports excellence at the Thailand National Sports University into practice was validated by experts' opinions through a Focus Group.

Instruments

The research instruments were divided into 3 sets as follows:

1. *Instrument Set 1:* A semi-structured interview questionnaire was used in the first round. This interview was developed from the analysis and synthesis of relevant research documents, theoretical principles, and suggestions from experts' opinions. The research instrument was reviewed by 5 experts, and the Index of Item-Objective Congruence (IOC) for the questionnaire was found to be 0.86.
2. *Instrument Set 2:* A questionnaire for data collection using the EDFR technique was used in the second round. This was a closed-ended questionnaire with a 5-level

rating scale. The questions were derived from the responses of experts in the second round. This questionnaire was used with a group of 17 experts.

3. *Instrument Set 3*: A questionnaire for research using the EDFR technique in the third round. This was a closed-ended questionnaire with a 5-level rating scale that contained the same questions as in the second round. Additionally, it included statistical values such as the median of expert responses and the interquartile range to reflect the consistency of expert answers. It also showed the positions of each expert's responses based on the second round.

Data Collection

The researchers conducted data collection as follows:

1. Requested a letter from the Faculty of Education, Thailand National Sports University Trang Campus, to seek cooperation from experts and the information group for data collection.
2. Gathered basic information on the mechanisms for driving the national strategy for promoting sports excellence of the Thailand National Sports University into practice.
3. Synthesized and set the framework for interview questions based on the study of the mechanisms for driving the national strategy for promoting sports excellence of the Thailand National Sports University into practice. Then, the researchers created a semi-structured interview to interview 5 experts and collected the data personally.
4. Synthesized the results from the first-round expert interviews and developed a 5-level rating scale questionnaire based on the main framework of the mechanisms for driving the national strategy for promoting sports excellence of the Thailand National Sports University into practice.
5. Created an online questionnaire using Google Document (G-Mail) for convenience, speed, and ease of response, which was sent to 17 experts in the second round and received responses via the internet. Some data were collected personally by the researchers, and responses were sent back through electronic mail.
6. Selected statements from the second-round questionnaire that had a median score of 3.50 or higher and an interquartile range of 1.50 or less. These statements were used to create a third-round questionnaire with the same questions as the second round, but included the median, interquartile range, and the response positions from the second round. This allowed the experts to confirm or change their responses and provide reasons if their scores were outside the interquartile range. The responses were collected via electronic mail.
7. Synthesized the consensus opinions from the experts to create a guide for the mechanisms for driving the national strategy for promoting sports excellence of the Thailand National Sports University into practice.

8. Organized a Focus Group discussion by inviting 11 experts involved in the main missions of the mechanisms for driving the national strategy for promoting sports excellence of the Thailand National Sports University into practice, as well as stakeholders. The researchers facilitated the discussion to reach consensus and acceptance of the feasibility and trends of the mechanisms.
9. Summarized and presented the mechanisms for driving the national strategy for promoting sports excellence of the Thailand National Sports University into practice, incorporating the experts' suggestions, and compiled a complete research report.

Statistical Analysis

The data analysis was conducted using both quantitative and qualitative methods as follows:

1. Analyzed the initial basic data and responses from the 5 experts using content analysis from the interviews and questionnaires.
2. Analyzed the responses from the experts in the second round using the Delphi technique, calculating the median, the difference between the median and mode, and the interquartile range (IQR) for each response. Displayed the positions of the median, mode, IQR, and each expert's responses were used in the third round of questioning.
3. Analyzed the responses from the experts using the Delphi technique in the third round.
4. Calculated the median, the difference between the median and mode, and the IQR for each response, using the following criteria for the Median, used the open-ended questionnaire responses to study, analyze, and create questions for a 5-level rating scale questionnaire.

Quality Assurance and Ethical Considerations

In this research study, the consent of the Sample Group was paramount. The Sample Group was selected to match the research objectives. The researchers obtained ethics approval for the research project involving human subjects, as reviewed and certified by the Ethics Committee under certificate number TNSU-EDU 006/2567. All the participants were informed of the conditions and voluntarily agreed to participate in the research study. The researchers explained the research details and provided a consent form that was signed by the participants. The consent process included obtaining consent from the volunteers and/or their legal representatives.

RESULTS

This research involved studying documents, related research, and conducting in-depth interviews with 5 key informants, including the President of the Thailand National Sports University, the Director of the Sports Authority of Thailand (2022), the President of the Thai Sports Association, and 2 stakeholders who are experts in the field of sports. The findings revealed that the mechanisms for driving the national strategy for promoting sports excellence

comprised of **7 Aspects**: (a) Management; (b) Planning and Driving; (c) Budget Management; (d) Personnel Management; (e) Awareness and Recognition Building; (f) Integration and Participation; and (g) Monitoring and Evaluation.

The research findings indicate that the mechanisms for driving the national strategy for promoting sports excellence of the Thailand National Sports University into practice included 7 Aspects with a total of 58 components. A summary of the most agreed-upon statements by the experts is as follows:

Aspect 1: Management - The management aspect included 10 components, all of which the experts agreed upon, which showed consensus on all items.

Aspect 2: Planning and Driving - The planning and driving aspect included 10 components, all of which the experts agreed upon, which showed consensus on all items.

Aspect 3: Budget Management - The budget management aspect included 6 components, all of which the experts agreed upon, which showed consensus on all items.

Aspect 4: Personnel Management - The personnel management aspect included 11 components, all of which the experts agreed upon, which showed consensus on all items.

Aspect 5: Awareness and Recognition Building - The awareness and recognition building aspect included 5 components, all of which the experts agreed upon, which showed consensus on all items.

Aspect 6: Integration and Participation - The integration and participation aspect included 8 components, all of which the experts agreed upon, which showed consensus on all items.

Aspect 7: Monitoring and Evaluation - The monitoring and evaluation aspect included 8 components, all of which the experts agreed upon, which showed consensus on all items.

DISCUSSION

The findings regarding the mechanisms for driving the national strategy for promoting sports excellence at the Thailand National Sports University into practice are as follows:

1. Management

It was found that there should be policy formulation, guidelines, and long-term planning directions (5 to 10 years). There should be a clear vision for sports excellence. The operational plans should align with the university's sports excellence development plans. For instance, each campus could focus on one specific sport to allow students with specific sports talents to choose appropriate campuses. This finding is consistent with Izzicupo et al. (5), who studied the strategic development of the University of Technology in Jamaica with the purpose to create the best student-athletes in the world. The model included long-term contracts for coaches to prepare teams and competitions, annual training programs for coaches aiming at high-level athlete development, and creating online special courses for the athletes. This allowed direct learning from teachers and offered additional welfare to motivate the athletes, coaches, and related sports personnel. Similarly, Andryushchenko and Filimonova (2) found that cooperation

between the public and the private sectors would enhance sports funding from non-budgetary sources, and theoretical and practical provisions for university sports needed improvement.

2. Planning and Driving

There should be operational plans that align with the university's objectives and policies to compete in sports for excellence. Short-term and long-term plans leading to the development of sports for excellence should be established. This aligns with Kaewmanee and Kheovicai (7), who emphasized the necessity of short, medium, and long-term planning in higher education sports excellence programs. The organizational policies and plans should align with the national sports development plan for excellence. Strategic objectives should be achievable, with specific plans and goals for preparing teams for national and international competitions. This finding is consistent with Izzicupo et al. (5), who studied the strategic development at the University of Technology in Jamaica. They found that student-athletes trained throughout the year to achieve success, and adequate resources such as personnel, budget, facilities, and equipment were essential. This also aligned with the research of Onlao et al. (12), who concluded that systematic and efficient management of sports facilities and equipment for each type of sport is crucial.

3. Budget Management

It was found that budget usage in various departments should be tightly controlled and appropriate according to the planned projects. There should be practical guidelines specifying the scope of operations, plans, and budgets that adhered to accuracy and propriety that can be audited. There should be a spending plan for the received funds, and budget planning should be done on an annual or quarterly basis to ensure that the expenditures aligned with the objectives. Control measures for budget disbursement should also be established. This aligns with the research by Onlao et al. (12), which concluded that budget expenditure planning should have clear systems and mechanisms that covered the sports competition calendar throughout the year. The priority, necessity, and urgency of activities requiring budgets should be monitored to ensure they adhere to the set plans, and the expenses in various departments should be strictly controlled.

4. Personnel Management

It was found that personnel assignment should be based on the competence of individuals involved in sports operations. There should be criteria for evaluating academic positions based on sports expertise. This aligns with the study by Singcram and Thanaiudompat (16) that suggested that universities should establish specific units reporting directly to top management, which involved a committee of stakeholders. Sports coaches in each sport should be promoted based on their expertise. There should be processes for selecting domestic and international experts, consistent with the study by Srichaisawat (17), which analyzed the model of the Athletics Association of Thailand for selecting and recruiting highly capable athletes and coaches, and involving knowledgeable and experienced staff to join the team to enhance the chances of success. Coaches should have the opportunity to fully select athletes and should be sent to various training courses. Sports equipment for excellence should be separated from general teaching or service equipment, which is consistent with the study by Rakwongthai et al. (14) that found sports facilities, equipment, and convenience should meet safety standards for use.

5. Awareness and Recognition

It was found that the information technology system connecting networks should be further developed. Operational data should be disclosed to staff, aligning with the research by Jarumetheechon et al. (6), who studied participation and encouraged everyone to share opinions, make joint decisions, and exchange knowledge. Movement updates and performance monitoring should be available. Information should be publicized to relevant personnel, and the university's sports development, promotion, and support in all aspects should be known. This aligns with Meechat (9), who stated that organizational components should be divided into main functional groups responsible for the organization's core tasks and support groups that assist in the main tasks.

6. Integration and Participation

It was found that strategic plans for sports development should be adjusted, and various facilities should be systematically provided in sports fields to serve university athletes aiming for excellence. There should be integration of sports or related activities within university events, involving capable sports personnel from both the Thailand National Sports University and sports schools in developing sports excellence. This aligns with Chamnanchan et al. (3), who emphasized the importance of participation, allowing stakeholders to be involved in educational management activities, from problem analysis, planning, decision-making, problem-solving, to joint evaluation, ensuring effective educational management based on principles of shared thinking, doing, monitoring, and responsibility. There should also be direct data management responsibility for athletes, which is consistent with De Bosscher (4), who researched building athlete excellence in national competitions, and found that developing networks with sports organizations and involving stakeholders in policy and plan formulation, implementation, and evaluation are very important for achieving excellence in national sports competitions.

7. Monitoring and Evaluation

It was found that there should be control and monitoring of operations according to the plan, with clear indicators for sports excellence management. Annual reviews and improvements of the strategy and success in sports development should be conducted. Monitoring and evaluation of training and competition results should be used to plan athlete development. This is in line with Sorrahong and Jongkorkorn (15), who stated that performance evaluation provides guidelines for improvement in future operations. The process should include periodic evaluations of different aspects of athlete performance at the center of sports excellence, which also allows for the comparison of the results with set goals. This aligns with Liu et al. (8), who stated that analyzing and evaluating competition results is a factor contributing to the success of athlete development for excellence. Continuous monitoring, evaluation, and application of results for ongoing improvement is also supported by Kaewmanee and Kheovicai (7), who suggested that promoting sports excellence in universities should include performance evaluation systems for ongoing development.

CONCLUSIONS

The study concludes that the effective implementation of the national strategy for promoting sports excellence at the Thailand National Sports University requires an integrated management mechanism. This involves clear policies and long-term planning, systematic budget control, and competency-based personnel management. Equally important are the development of information systems to enhance awareness, stakeholder participation and

integration across related sectors, and continuous monitoring and evaluation with clear indicators. Collectively, these mechanisms strengthen the university's capacity to drive sustainable sports excellence at both the national level and the international level.

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Comparison of Weighted Jump Training in Different Directions on Leg Muscle Power in Female Youth Aged 14-16 Years

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Abstract

Noopayan P, Sukdee N, Suksuwan C. Comparison of Weighted Jump Training in Different Directions on Leg Muscle Power in Female Youth Aged 14-16 Years. The purpose of this study was to investigate and compare the effects of weighted jump training in different directions on leg muscle power in female youth volleyball players aged 14-16 years. The participants consisted of 30 female volleyball players from Bangkok Sports School who met the admission criteria for athlete training programs and were selected using purposive sampling. The participants were then randomly assigned into 3 groups of 10 subjects each: (a) Experimental Group 1 performed weighted forward and backward jump training; (b) Experimental Group 2 performed weighted lateral jump training to the left and right directions; and (c) the Control Group followed their regular training program. The training program lasted for 8 weeks, with 3 sessions per week on Monday, Wednesday, and Friday from 4:30 p.m. to 6:30 p.m. at Bangkok Sports School (Din Daeng Campus). Training loads were set at 20%, 25%, 30%, and 35% of body mass (BM), increasing every 2 weeks throughout the intervention period. Leg muscle power variables assessed included jump height, peak power, peak force, and peak velocity. The data were analyzed using mean, standard deviation, paired *t*-test, one-way analysis of variance (One-way ANOVA), and Bonferroni *post hoc* comparisons at a significance level of .05. The results indicated that after 8 weeks of training, Experimental Group 1 demonstrated significantly greater improvements in all leg muscle power variables compared with Experimental Group 2 and the Control Group ($P < .05$). Bonferroni *post hoc* analysis revealed that Experimental Group 1 showed significantly higher values in all variables than the Control Group ($P < .05$), and significantly greater peak velocity than Experimental Group 2 ($P < .05$). Although Experimental Group 2 demonstrated improvements in all variables compared with the Control Group, the differences were not statistically significant ($P > .05$). Furthermore, within-group comparisons showed that Experimental Group 1 significantly improved in all measured variables after training ($P < .05$); whereas, Experimental Group 2 and the Control Group showed improvements without statistically significant differences.

Keywords: Female Volleyball Players, Leg Muscle Power, Peak Force, Peak Power, Peak Velocity, Weighted Jump Training

INTRODUCTION

Volleyball is one of the most popular sports worldwide, and it is characterized by the presence of a net separating two opposing teams. Players are required to perform various technical skills, including passing, spiking, and defending against opponents' attacks. The nature of volleyball involves repeated bouts of high-intensity activity interspersed with periods of lower-intensity activity and recovery. Consequently, successful volleyball performance depends on multiple components of physical fitness, including muscular strength, speed, agility, endurance, and in particular muscular power, which is a key determinant of jumping ability and rapid movement during competition (5).

Jumping is considered one of the most fundamental skills in volleyball, playing a critical role in both offensive and defensive situations. Skills such as the spike jump, blocking jump, and jump setting all require excellent jumping performance. Jumping ability has been recognized as an important indicator of athletic performance in volleyball players for many years. Furthermore, high-level competition requires athletes to change direction rapidly and efficiently in forward, backward, and lateral movements to respond effectively to constantly changing game situations.

Although height and anthropometric characteristics provide competitive advantages, particularly for front-row players and net play, jumping ability and lower-limb muscular power are physical qualities that can be substantially improved through appropriate training. In fact, it is common knowledge that elite volleyball players generally possess superior body size and muscular strength, while members of some men's national volleyball team have an average height of 6 and one-half feet. Hence, for athletes with limitations in body size, improvements in lower-limb power and jumping ability can significantly enhance competitive performance.

Various training methods have been employed to improve lower-limb muscular power, including resistance training, plyometric training, and combinations of these approaches. Intraporn (8) suggested that both resistance and plyometric training are effective for enhancing muscular power, particularly when integrated into combined training methods such as weighted plyometric exercises, plyometric training with external loads, or complex training. It is common knowledge that such training produces significant improvements in muscular power and overall athletic performance (7).

In recent years, loaded jump training has gained considerable attention in sports science because of its effectiveness in enhancing explosive muscular power. Training with external loads equivalent to approximately 20 to 35% of body mass has been identified as an optimal intensity for simultaneously improving muscular power and contraction velocity. Cormie, McGuigan, and Newton (3) explained that moderate external loads enable athletes to maximize both force and movement velocity, which are the two primary components of muscular power. Similarly, Loturco et al. (11) reported that loaded jump training using approximately 20 to 40% of body mass significantly improved movement velocity and muscular power, particularly in explosive sports such as volleyball and soccer.

In addition to training intensity, the direction of movement has emerged as another important factor influencing athletic performance. In fact, it is important to emphasize

multidirectional training, given that sports performance rarely involves movement in only one plane, and it is especially since multidirectional plyometric training more closely replicates the neuromuscular demands of actual sports competition.

For youth athletes, training program design must also consider growth and maturation, as children and adolescents are not simply smaller versions of adults. Age-appropriate training programs promote physical development while minimizing the risk of injury, which is in agreement with Malina et al. (12) who reported that properly designed strength and plyometric training programs are both safe and effective in improving strength, speed, and muscular power in youth athletes.

Despite the growing body of strength training literature investigating the effects of resistance and plyometric training on muscular power (4), relatively few studies have specifically compared the effects of loaded jump training performed in different movement directions among female youth volleyball players. In particular, evidence comparing forward–backward loaded jump training with lateral loaded jump training remains limited, although both movement patterns frequently occur during volleyball competition.

Therefore, the purpose of this study was to investigate the effects of loaded jump training performed in different movement directions on lower-limb muscular power in female youth volleyball players aged 14-16 years. The findings are expected to identify the most effective training method for improving athletic performance in youth volleyball players and to provide practical guidance for coaches in designing sport-specific training programs that optimize lower-limb power development and competitive performance.

METHODS

Population and Sample

The population consisted of 60 female volleyball players who were 14 to 16 years of age. As athletes, they were under the Ministry of Tourism and Sports, local administrative organizations, and the Bangkok Metropolitan Administration (BMA). All the participants had been selected to compete in regional or national volleyball competitions, and they possessed comparable levels of playing ability.

The sample consisted of 30 female volleyball players aged 14 to 16 years from Bangkok Sports School. They were selected using purposive sampling based on the study's Inclusion Criteria. The participants were subsequently randomly assigned to 3 Groups of 10 subjects in each Group using simple random assignment.

The intervention lasted 8 weeks. The training groups were organized as follows: (a) the Experimental Group 1 performed loaded forward–backward jump training; (b) the Experimental Group 2 performed loaded lateral jump training (left–right); and the (c) the Control Group that continued the regular volleyball training program without additional loaded jump training.

Inclusion Criteria

1. Female volleyball players aged 14-16 years who regularly participated in competitive volleyball training.

2. Free from musculoskeletal injuries or medical conditions that could interfere with training or testing.
3. No history of anabolic steroid use, performance-enhancing drugs, or illicit substances.
4. Possessed sufficient baseline lower-body strength, demonstrated by the ability to perform a squat with a load between 1.5 and 2.0 times their body mass.
5. Voluntarily agreed to participate in the study and provided written informed consent.
6. Did not participate in any other research project or additional structured training program during the study period.

Exclusion Criteria

1. Withdrew their consent at any stage of the research.
2. Attended fewer than 80% of the scheduled training sessions.
3. Were unable to complete the study because of illness, injury, or other unforeseen circumstances.

Research Instruments

The instruments used in this study consisted of 2 categories: Experimental Equipment and Data Collection Instruments.

1. ***Experimental Equipment.*** The equipment and training program used to improve lower-limb muscular power included: (1.1) A 40-cm plyometric box for jump training; (1.2) Kettlebells used as external resistance during loaded jump exercises; (1.3) Dumbbells used as additional resistance equipment; and (1.4) An 8-week loaded jump training program with training loads progressing from 20% to 35% of body mass (BM), increasing every 2 weeks. Each session consisted of 4 sets of 6 repetitions, with 1 minute of rest between the sets. Training was performed 3 sessions per week throughout the intervention period.
2. ***Data Collection Instruments.*** Lower-limb muscular power was assessed using the following equipment: (2.1) FT-700 Power System (Fitness Technology, Australia), used to measure lower-limb muscular power variables; (2.2) Ballistic Measurement System Version 2011 (Fitness Technology, Australia), used for recording and analyzing performance variables; and (2.3) The study was conducted at Bangkok Sports School (Thai-Japanese Din Daeng Campus), Bangkok, Thailand.

Operational Definitions

The effects of different loaded jump training protocols on lower-limb muscular power refer to the investigation and comparison of different loaded jump training modalities and their effects on lower-limb muscular power in female youth volleyball players aged 14-16 years. The outcomes were evaluated using the following performance variables: (a) jump height; (b) peak power; (c) peak force; and (d) peak velocity.

Different loaded jump training protocols refer to jump training performed with external resistance in two different movement directions: (1) Forward-Backward Jump – loaded jumps performed alternately in the forward and backward directions; and (2) Lateral Jump – loaded jumps performed alternately to the left and right sides.

Lower-limb muscular power refers to the ability of the leg muscles to generate maximal explosive force within a short period of time for jumping and volleyball-specific movements. In this study, lower-limb muscular power was assessed using the FT-700 Power System (6).

Female youth volleyball players aged 14-16 years refer to female volleyball athletes aged 14-16 years who were affiliated with Bangkok Sports School, met the study's inclusion criteria, and were recruited as participants. A total of 30 athletes were randomly assigned into 3 Groups, with 10 participants in each Group.

Training program refers to an 8-week loaded jump training program designed to improve lower-limb muscular power. The program specified the frequency, intensity, and volume of training sessions involving loaded jumps performed in different movement directions.

Data Analysis

The data were analyzed to investigate and compare the effects of loaded jump training performed in different movement directions on lower-limb muscular power in female youth volleyball players aged 14-16 years. Statistical analyses were conducted using a computerized statistical software package as follows:

1. Descriptive statistics that also included the mean (M) and standard deviation (SD) were calculated to summarize participant characteristics and lower-limb muscular power variables.
2. One-way Analysis of Variance (One-way ANOVA) was used to compare the differences in lower-limb muscular power variables among the 3 Groups following the 8-week training intervention. When significant differences were identified, Bonferroni *post hoc* comparisons were performed to determine pairwise differences between the Groups.
3. Paired-samples *t*-test was used to compare pre-test and post-test measurements within each Group.
4. Statistical significance was established at the .05 level ($P < .05$) for all analyses.

RESULTS

Table 1. Comparison of Lower-Limb Muscular Power Among the 3 Groups After the 8-Week Intervention.

Variables	After the 8-Week Training Program			F	P
	Experimental Group 1	Experimental Group 2	Control Group		
1. Jump Height (cm)	10.97	10.82	10.79	3.55	0.04*
2. Peak Power (W)	7540.09	7531.84	7529.30	4.57	0.02*
3. Peak Force (N)	2182.14	2176.01	2173.10	4.04	0.03*
4. Peak Velocity (m/s)	7.87	7.76	7.72	4.08	0.03*

*P < .05

As presented in Table 1, after the 8-week intervention, the Experimental Group 1 demonstrated the highest mean values for jump height, peak power, peak force, and peak velocity, followed by the Experimental Group 2 and the Control Group, respectively. Significant differences were observed among the 3 Groups for all measured variables ($P < .05$).

Table 2. Within-Group Comparison of Lower-Limb Muscular Power Before and After the 8-Week Intervention in Experimental Group 1.

Variables	Pre-Training		Post-Training (8 Weeks)		t	P
	Mean	SD	Mean	SD		
1. Jump Height (cm)	10.70	0.14	10.97	0.11	-5.54	.00*
2. Peak Power (W)	7521.80	6.42	7540.09	9.25	-6.04	.00*
3. Peak Force (N)	2168.14	7.28	2182.14	6.40	-4.34	.00*
4. Peak Velocity (m/s)	7.69	0.08	7.87	0.23	-4.55	.00*

* P < .05

As shown in Table 2, the participants in the Experimental Group 1 exhibited significant improvements in jump height, peak power, peak force, and peak velocity following the 8-week training program compared with their pre-training values ($P < .05$).

Table 3. Within-Group Comparison of Lower-Limb Muscular Power Before and After the 8-Week Intervention in the Experimental Group 2.

Variables	Pre-Training		Post-Training (8 weeks)		<i>t</i>	<i>P</i>
	Mean	SD	Mean	SD		
1. Jump Height (cm)	10.76	0.14	10.82	0.22	-2.03	.07
2. Peak Power (W)	7524.79	6.68	7531.84	8.70	-1.61	.14
3. Peak Force (N)	2169.22	8.07	2176.01	8.20	-2.03	.07
4. Peak Velocity (m/s)	7.71	0.07	7.76	0.11	-1.45	.18

* $P < .05$

As presented in Table 3, the Experimental Group 2 showed slight increases in the mean values of jump height, peak power, peak force, and peak velocity after the 8-week training program. However, none of the improvements reached statistical significance ($P > .05$).

Table 4. Within-Group Comparison of Lower-Limb Muscular Power Before and After the 8-Week Intervention in the Control Group.

Variables	Pre-Training		Post-Training (8 weeks)		<i>t</i>	<i>P</i>
	Mean	SD	Mean	SD		
1. Jump Height (cm)	10.78	0.11	10.79	0.13	-0.18	.86
2. Peak Power (W)	7526.33	7.08	7529.30	6.91	-0.99	.35
3. Peak Force (N)	2171.44	8.70	2173.10	7.06	-0.60	.57
4. Peak Velocity (m/s)	7.71	0.13	7.72	0.14	-0.30	.77

* $P < .05$

As shown in Table 4, the participants in the Control Group demonstrated only minimal increases in the mean values of jump height, peak power, peak force, and peak velocity after the 8-week period. No statistically significant differences were observed between the pre-test and post-test measurements for any of the variables ($P > .05$).

Between-Group Comparisons

Before the training program, no significant differences were found among Experimental Group 1, Experimental Group 2, and the Control Group in jump height, peak power, peak force, and peak velocity. These findings indicate that the 3 Groups had comparable baseline levels of lower-limb muscular power.

After the 8-week training program, significant differences ($P < .05$) were observed among the 3 Groups in jump height, peak power, peak force, and peak velocity. These results indicate that different loaded jump training programs produced different effects on the development of lower-limb muscular power in female youth volleyball players.

Bonferroni *post hoc* comparisons revealed that the Experimental Group 1 demonstrated significantly greater values than the Control Group in all measured variables, including jump height, peak power, peak force, and peak velocity ($P < .05$). In contrast, the Experimental Group 2 did not differ significantly from the Control Group in jump height, peak power, or peak force.

Within-Group Comparisons

The Experimental Group 1 showed significant improvements ($P < .05$) in jump height, peak power, peak force, and peak velocity following the 8-week training program. These findings indicate that the loaded forward–backward jump training program effectively enhanced all components of lower-limb muscular fitness and power (13), including jumping performance, power production, maximal force, and contraction velocity.

The Experimental Group 2 showed slight increases in the mean values of jump height, peak power, peak force, and peak velocity after training; however, the improvements were not statistically significant ($P > .05$). This suggests that the loaded lateral jump training program was insufficient to produce substantial improvements in lower-limb muscular power.

The Control Group demonstrated no significant differences ($P > .05$) between the pre-training and the post-training measurements in any of the measured variables. These findings were expected because the participants continued their regular volleyball training without receiving a specialized loaded jump training program.

DISCUSSION

The present study found no significant differences in jump height, peak power, peak force, or peak velocity among the 3 Groups before the training intervention, which indicated that the participants were homogeneous at baseline and that no confounding effects existed prior to the experiment. Following the 8-week intervention, significant differences were observed among the Groups for all 4 variables, with the subjects in the Experimental Group 1 demonstrating the highest values in every performance measure. These findings indicate that the loaded forward–backward jump training program was the most effective intervention for improving lower-limb muscular power. Also, the findings are consistent with Thepparit (14), who reported that a 10-week plyometric training program significantly improved lower-limb muscular power, as measured by the vertical jump and standing long jump tests. These improvements may be explained by the enhanced function of the stretch–shortening cycle (SSC) that plays a critical role in increasing explosive muscular power.

However, the present findings differ from those reported by Intiraporn (8), who found no significant differences among plyometric training combined with resistance training, weighted plyometric training, and complex training. These discrepancies may be attributed to differences in participant characteristics, training duration, or training intensity. Furthermore, Baker et al. (1) reported that jump training performed with approximately 55% of one-repetition maximum (1RM) produced maximal power output, supporting the concept that training intensity is a major determinant of power development. Therefore, the superior performance of the Experimental Group 1 may be attributed to the appropriate combination of training intensity, volume, and sport-specific movement patterns, which facilitated greater neuromuscular adaptations.

The significant improvements observed in the Experimental Group 1 are also consistent with the findings of Kimwaha (10), who reported that resistance training significantly increased lower-limb explosive power when an appropriate training load was applied. Likewise, Intiraporn (9) found that loaded jump training using 20-30% of 1RM was more effective for improving muscular power than lower training intensities, supporting the overload principle. International studies have reported similar findings. Wong et al. (15) demonstrated that combined strength and power training significantly improved vertical jumping performance, which is consistent with the increased jump height observed in Experimental Group 1. In contrast, Christopher et al. (2) reported that resistance training, plyometric training, and complex training all improved muscular strength, although no significant differences were observed among the training methods. These findings suggest that training effectiveness depends not only on the type of exercise but also on the appropriateness of the training program and its implementation.

From a physiological perspective, the improvements observed in the Experimental Group 1 can be explained by neuromuscular adaptation, including enhanced motor unit recruitment, increased neural firing frequency, and improved synchronization of muscle activation. These adaptations enable the muscles to generate greater force within a shorter period of time. Moreover, the increase in peak velocity reflects improvements in the function of fast-twitch muscle fibers, which are essential for explosive movements such as spiking, blocking, and rapid changes of direction during volleyball competition. The results may also be explained by improvements in the stretch-shortening cycle (SSC), which enhances the storage and utilization of elastic energy during rapid eccentric-concentric muscle actions, thereby increasing jump height and muscular power. Conversely, the absence of significant improvements in Experimental Group 2 suggests that the training stimulus may not have been sufficient to induce meaningful physiological adaptations. This finding is consistent with the Specific Adaptation to Imposed Demands (SAID) principle, which states that physiological adaptations are highly specific to the type, intensity, and direction of the training stimulus.

CONCLUSIONS

From a practical perspective, the findings suggest that training programs capable of simultaneously enhancing force production and movement velocity are highly effective for improving volleyball-specific performance, particularly spiking, blocking, and rapid directional changes. Therefore, volleyball coaches should design training programs that

appropriately manipulate training intensity, volume, frequency, and movement specificity to maximize athletic performance while adhering to established principles of sports science.

Recommendations

Since the loaded forward–backward jump training program effectively improved lower-limb muscular power, volleyball coaches and physical education teachers are encouraged to incorporate this program into training sessions to enhance athletes' jumping ability and explosive movement performance. The training program should be modified according to the athletes' level of performance, such as secondary school students, university athletes, or elite players, to maximize training effectiveness.

Future studies should include larger sample sizes and more diverse participant populations, including different sexes, age groups, and competitive levels to improve the generalizability of the findings. Future research should investigate additional volleyball-related performance variables, such as agility, sprint speed, change-of-direction ability, and other physical fitness components to provide a more comprehensive understanding of the effects of loaded jump training.

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