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A Systematic Review of the Biomechanical Impact of Load Carriage on Gait in Older Adults

Objective: To examine the biomechanical effects of load carriage on gait patterns, joint kinematics, and muscle activity during walking in older adults. Methods: A systematic literature search was conducted across five databases (CNKI, Wanfang, VIP, PubMed, and Web of Science) through June 2025. Eight studies met the inclusion criteria. The methodological quality of included studies was assessed using the ROBINS-I Version 2 tool. Results: Asymmetrical load carriage during walking increases step frequency and step width, shortens step length and the gait cycle, induces lateral trunk tilt, and leads to asymmetric muscle activation between body sides. With increasing load, adverse effects on trunk posture and muscle activation become more pronounced, including a significant increase in contralateral hip joint torque. Symmetrical load carriage up to 5% of body weight has no significant effect on gait and may improve static postural stability in older adults. Conclusion: Both asymmetrical and heavier load carriage impose greater biomechanical demands on gait in older adults. Older adults are advised to carry loads symmetrically and keep the weight below 5% of body mass to maintain gait stability and reduce fall risk.

Keywords: Load Carriage, Older Adults, Gait, Systematic Review, Biomechanics, Dynamic Stability, Fall Risk

Introduction

The aging process causes a progressive decline in physical functions, including motor ability and neurological integrity, thereby significantly increasing fall risk among older adults [1]. Globally, falls are a significant public health concern, causing approximately 684,000 deaths annually and ranking as the second leading cause of unintentional injury-related mortality [2]. Robinovitch et al. reported that 24% of all falls in older adults occurred during normal forward walking—the highest proportion among all fall scenarios [3].

Various factors contribute to fall risk during walking, including motor ability, psychological state, and environmental conditions [4]. Load carriage constitutes an environmental modification and is a routine aspect of daily life for many older adults. Carrying external loads shifts the body’s center of mass by introducing additional external forces. To maintain balance, individuals must adjust their gait and posture accordingly. Consequently, the biomechanical characteristics of load-carrying gait differ significantly from those of unloaded walking [5].

There are currently divergent perspectives regarding the effects of load carriage on gait in older adults. One perspective posits that load carriage compromises gait stability in older adults. For example, Nagaraja et al. found that during load-bearing walking, the trunk and pelvis deviate from the neutral position, increasing asymmetry in frontal and transverse plane movements and disrupting the rhythmic coordination between trunk and pelvic motion [6]. These biomechanical changes clearly impair the ability of older adults to maintain stable gait. In contrast, an alternative viewpoint argues that load carriage may not negatively affect gait in older adults and could even enhance postural stability during quiet standing [7].

Load carriage during walking is sometimes unavoidable for older adults, such as when carrying items from routine shopping trips. Therefore, understanding the biomechanical alterations induced by load carriage is crucial for reducing fall incidence and promoting both physical and mental well-being in later life.

Existing research on gait in older adults has primarily focused on walking under cognitive load, whereas empirical evidence concerning walking under external physical load remains limited. Although studies on load-bearing gait in older adults are scarce, those available vary in testing tools, evaluation metrics, and measurement dimensions, resulting in inconsistent findings.

Methods and materials

This review was conducted and reported following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [8].

Search Strategy

A comprehensive literature search was conducted across five databases—PubMed, Web of Science, CNKI, Wanfang, and VIP—with the search period extending through June 2025. The search terms included combinations of the following keywords: "older", "load", "carrying", "bags", "weight-bearing", "walking", "gait", "biomechanics", and "biomechanical". Using PubMed as an example, the detailed search strategy was as follows: ((older[Title/Abstract]) AND (load[Title/Abstract] OR carrying[Title/Abstract] OR bags[Title/Abstract] OR weight-bearing[Title/Abstract])) AND (walking[Title/Abstract] OR gait[Title/Abstract] OR biomechanics[Title/Abstract] OR biomechanical[Title/Abstract])

The search was restricted to controlled experimental studies published in peer-reviewed academic journals in either Chinese or English.

Inclusion and Exclusion Criteria

Inclusion Criteria:

(1) Participants were healthy older adults aged 60 years or older.

(2) Participants walked in a straight line, at a self-selected speed, within a defined experimental setting while facing forward throughout the task.

(3) Outcome measures included, but were not limited to:

(a) kinematic indicators (e.g., joint angles, center of pressure displacement, and center of mass sway amplitude);

(b) kinetic indicators (e.g., joint moments, ground reaction forces (GRF), and joint power);

(c) gait parameters (e.g., step length, stride length, gait cycle, step width, cadence, gait speed, and gait variability coefficient).

Exclusion Criteria:

(1) Participants were older adults diagnosed with medical conditions such as Parkinson's disease, Alzheimer's disease, or hypertension.

(2) Studies in which the intervention was unrelated to load carriage or involved non-standard walking tasks.

(3) Studies published in languages other than Chinese or English; conference abstracts, retrospective analyses, reviews, or those with inaccessible full texts.

(4) Duplicate publications or those assessed as having low methodological quality. (5) Studies lacking extractable or usable data.

Study Selection and Data Extraction

All retrieved records were imported into EndNote X9 for reference management.

(1) Duplicate records were identified and removed.

(2) Titles and abstracts were screened to exclude irrelevant studies.

(3) Full texts of potentially eligible articles were reviewed to exclude studies not meeting the inclusion criteria.

(4) Remaining eligible studies were included in the final analysis.

Extracted data included article title, first author, year of publication, country of origin, participant characteristics (age, sex, height, and weight), sample size, study design and grouping, and outcome measures.

Quality Assessment of Included Studies

The methodological quality of the included studies was evaluated using the ROBINS-I Version 2 tool [9].

The tool evaluates bias risk across seven domains: confounding, classification of interventions, participant selection, deviations from intended interventions, missing data, outcome measurement, and selection of reported results. Each domain is assessed using a structured set of signaling questions designed to guide risk-of-bias judgments [10].

Results and Discussion

Results of Literature Search

A total of 2,437 records were retrieved from five databases: CNKI (n = 114), Wanfang (n = 19), VIP (n = 6), PubMed (n = 615), and Web of Science (n = 1,683). An additional three studies were identified through manual reference screening. After removing 177 duplicates, 2,263 unique records remained for screening. After title and abstract screening, 2,196 records were excluded, leaving 67 articles for full-text review. Following full-text review, 59 articles were excluded, and eight studies were included in the final analysis (Bampouras et al., 2016; Narouei et al., 2023; Allahverdipour et al., 2021; Badawy et al., 2019; Walsh et al., 2018; Kong et al., 2014; Matsuo et al., 2008; Tengyu et al., 2018) [7, 11–16].

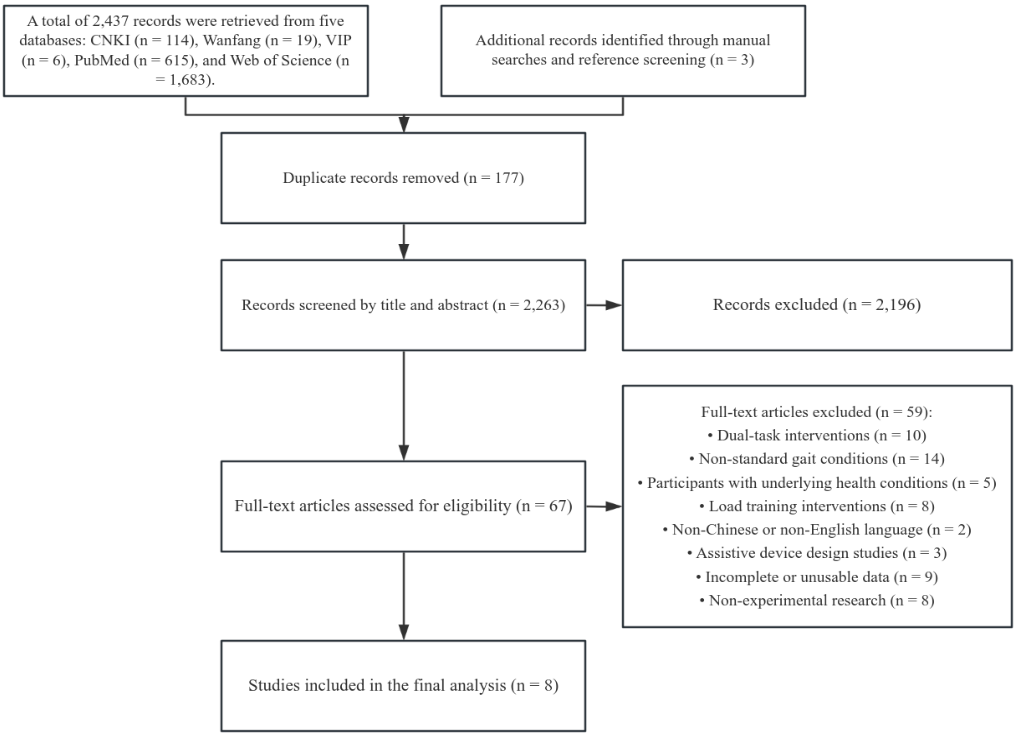

Figure 1. Flow Diagram of the Study Screening Process

Risk of Bias Assessment Results

According to the ROBINS-I Version 2 assessment criteria, Walsh et al. and Kong et al. clearly reported inclusion and exclusion criteria and effectively controlled for potential confounding factors. Consequently, the risk of bias due to confounding was judged to be low. Allahverdipour et al. (2021) and Kong et al. (2014) clearly described the inclusion procedures and participant recruitment methods, ensuring appropriate participant selection [12, 14, 15]. As a result, the risk of bias in participant selection was rated as low. However, both studies employed measurement tools susceptible to inaccuracies, resulting in a moderate risk of bias in outcome assessment. In all eight included studies, intervention conditions were clearly defined and appropriately classified. Participants adhered strictly to the assigned interventions, with no notable deviations from the intended procedures. All relevant outcomes were reported and supported by appropriate statistical validation. Accordingly, the risks of bias related to intervention classification, deviations from intended interven-

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tions, missing data, and selective outcome reporting were all judged to be low. Overall, the included studies were assessed to have a moderate risk of bias, which is considered acceptable for inclusion in this review.

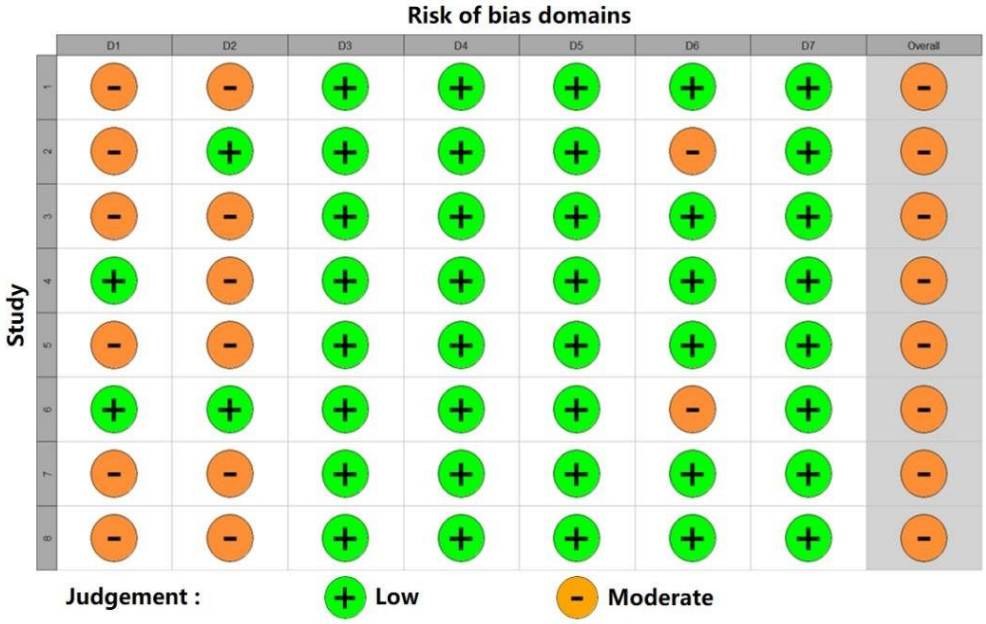

Figure 2. Risk of Bias Assessment Across Included Studies Using ROBINS-I Tool

Note: D1 = Risk of bias due to confounding; D2 = Risk of bias in selection of participants into the study; D3 = Risk of bias in classification of interventions; D4 = Risk of bias due to deviations from intended interventions; D5 = Risk of bias due to missing data; D6 = Risk of bias arising from measurement of the outcome; D7 = Risk of bias in selection of the reported result. 1: Narouei, S., 2023; 2: Allahverdipour, H., 2021; 3: Badawy, M., 2019; 4: Walsh, G. S. (2018); 5: Bampouras, T. M., 2016; 6: Kong, P. W., 2014; 7: Matsuo, T., 2008; 8: Zhang, T., 2018

Basic Characteristics of Included Studies

Table 1 summarizes the basic characteristics of the included studies. All eight studies were published between 2008 and 2023. All eight studies were published between 2008 and 2023. The studies originated from the United Kingdom (n = 2), Japan (n = 2), and one each from the United States, China, Singapore, and Iran. Collectively, the studies involved 278 healthy older adults. Regarding load carriage methods, four studies investigated bilateral hand-carrying, four involved unilateral carrying, two involved backpack-style carrying, one involved lower-limb loading, one included pushing and pulling carts, and one assessed front-carrying (e.g., cradling). Five studies implemented symmetrical loading, while another five assessed asymmetrical (unilateral) loading patterns.

Table 1

Summary of General Characteristics of the Included Studies

First Author	Year of Publication	Country	Sample Size (M/F)	Age (Years)	Height	Weight (kg)	Load Type (Weight)
Narouei, S.	2023	Japan	29(7,22)	67.96±6.86	157.63±8.48cm	53.78±9.04	No load; symmetrical load (2% body weight)
Allahverdipour, H.	2021	Iran	42(21,21)	≥60	Not reported	Not reported	No load; symmetrical loads (2, 4, 6 kg)

Continuation of Table 1

First Author	Year of Publication	Country	Sample Size (M/F)	Age (Years)	Height	Weight (kg)	Load Type (Weight)
Badawy M.	2019	USA	20(20,0) 5(5,0)	59.7±3.5	175.3±4.4cm	70.2±6.6	No load; asymmetrical load (5.67 kg, 10.21 kg)
Walsh, G. S.	2018	UK	14(7,7)	65.0±6.0	1.70±0.10m	74±13	No load; stable/unstable asymmetrical load (15% body weight)
Bampouras, T. M.	2016	UK	19(0,19) 9(0,9)	71.0±6.0	1.65±0.06m	66.3±10.1	No load; asymmetrical loads (1.5 kg, 3 kg); symmetrical loads (3 kg, 6 kg)
Kong, P. W.	2014	Singapore	52(24,28) 32(14,18)	69.4±7.0	1.57±0.08m	62.5±10.0	No load; pushing load (10 kg), pulling load (15 kg); symmetrical load (4 kg)
Matsuo, T.	2008	Japan	11(0,11) 6(0,6)	59.7±1.4	1.61±0.06m	56.8±4.7	No load; single-hand carrying (3 kg, 8 kg)
Zhang, T.	2018	China	15(8,7)	71.43±4.72	Not reported	Male: 70.21 ± 6.10 kg; Female: 61.02 ± 9.47 kg	No load; symmetrical/asymmetrical load (10% body weight)

All included studies employed an experimental design.

Selection of Research Instruments and Outcome Measures

The research instruments and outcome measures employed in the included studies are summarized in Table 2. Four studies employed three-dimensional motion capture systems; three utilized surface electromyography (sEMG); one used a high-speed camera with video analysis software; one implemented the Optojump system; and one relied on a stopwatch. The outcome measures were primarily categorized into gait parameters, joint kinematics, muscle activity, and miscellaneous variables. In terms of gait parameters, walking speed was assessed in three studies; cadence, stride time (ST), and total double support (TDS) were each reported in two studies; while step length (SL), step width (SW), coefficient of variation (CoV), and step asymmetry (SA) were each evaluated in one study. For joint kinematics, the angles of the hip, knee, ankle, and trunk joints were measured in two studies; center of pressure (CoP) displacement and peak hip abduction torque were each reported in one study. The Timed Up and Go (TUG) test duration was measured in one study.

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Table 2

Measurement Instruments and Outcome Variables in the Included Studies

Included Study	Instrument	Outcome Measures			
		Gait Parameters	**Joint Kinematics**	**Muscle Activity**	**Others**
Narouei, S., 2023	A three-dimensional motion capture system, and surface electromyography (sEMG) system	Cadence, and toe off timing	Hip, knee, and ankle joint angles	Normalized Average Value of EMG： rectus femoris (RF)	
Allahverdipour, H., 2021	Stopwatch				Timed Up and Go (TUG)
Badawy M., 2019	Surface electromyography (sEMG) system	Speed		Average and peak % maximum voluntary contraction (MVC)：left/right rectus abdominis (RA), left/right external oblique (EO), left/right internal oblique (IO), left/right latissimus dorsi (LD), left/right upper erector spinae (UES), and left/right lower erector spinae (LES)	
Walsh, G. S., 2018	A three-dimensional motion capture system, and surface electromyography (sEMG) system	Step width (SW), and stride time (ST)	Hip, knee, and ankle joint angles in the sagittal, frontal, and transverse planes	Mean electromyographic (EMG) activity：RF, vastus medialis (VM), biceps femoris (BF), tibialis anterior (TA), gastrocnemius medialis (GM), and soleus (SOL)	
Bampouras, T. M., 2016	Optojump, and treadmill	Stride length (SL), coefficient of variation (CoV), total double support (TDS), step asymmetry (SA), and gait stability Ratio (GSR)			
Kong, P. W., 2014	High-speed video camera, video analysis software, and timing gates	Start-up time, and speed			
Matsuo, T., 2008	A three-dimensional motion capture system, and three-dimensional force plate		Maximum trunk/head lateral flexion to contralateral side, maximum upper arm elevation for contralateral side, contralateral/ipsilateral maximum hip abduction torque, and continuous relative phase (CRP)		
Zhang, 2018	A three-dimensional motion capture system, and three-dimensional force plate	Cadence, speed, SL, ST, stance phase (SP), and COV	Center of pressure (CoP) displacement		

In experimental research in sports and human movement sciences, researchers typically select appropriate instruments and precise outcome measures based on study objectives, equipment accuracy, reliability, and cost, as well as the demands of data processing and analysis.

In this study, various technologies used to measure kinematic parameters operate on a shared fundamental principle: capturing the trajectories of anatomical landmarks to calculate motion-related variables. Their primary differences lie in technological sophistication and system evolution. Historically, motion capture began with Eadweard Muybridge's pioneering use of sequential photography to capture the dynamic movement of galloping horses—an approach later widely adopted for studying human locomotion. With the advent and widespread adoption of video technology, researchers began employing high-speed cameras and camcorders to record gait behavior. By analyzing sequential frames, they extracted spatiotemporal characteristics of movement. Kong et al. used high-speed video cameras and video analysis software to measure participants' initiation time and gait speed [15]. The emergence of digital and sensor technologies has enabled optical motion capture systems to record human walking trajectories with significantly enhanced precision. Bampouras et al. employed the Optojump system to measure step length (SL) and total support duration (TSD) during treadmill walking in older adults [7]. Similarly, Narouei et al. utilized a three-dimensional motion capture system to acquire gait parameters and joint angles [11]. The key distinction between the two systems lies in data dimensionality. The Optojump system measures temporal parameters by detecting light interruptions between emitter and receiver bars, enabling the assessment of contact time, flight time, and stride timing during walking, running, and jumping. In contrast, a three-dimensional motion capture system incorporates a Z-axis, enabling the capture of reflective marker trajectories on joints to derive multi-planar joint angles at the hip, knee, ankle, and trunk.

Among the included studies, three employed similar methodologies to measure lower-limb sEMG signals during load-carrying walking in older adults. However, due to differing experimental objectives, the selected muscles and evaluation metrics varied slightly. All three studies included the rectus femoris (RF) as a target muscle. Badawy et al. additionally included muscles such as the external oblique (EO), internal oblique (IO), and latissimus dorsi (LD) to investigate trunk muscle activation during movement [13]. Walsh et al. focused on comprehensive lower-limb muscle activity and thus included a broader array of lower-extremity muscles in their analysis. Regarding evaluation metrics, Narouei et al. and Walsh et al. [11, 14] conducted time-domain analysis of sEMG to calculate the average electromyographic amplitude, reflecting the mean activation levels of the measured muscles. In contrast, Badawy et al. normalized the EMG values of each muscle to the percentage of maximum voluntary contraction (MVC), emphasizing the relative intensity of maximal muscle recruitment [13].

Biomechanical Effects of Various Load-Carrying Methods on Gait in Older Adults

In the included studies, researchers frequently designed a range of load-carrying conditions to comprehensively assess the effects of load carriage on gait in older adults. Load carriage methods are typically categorized as symmetrical or asymmetrical based on the distribution of weight. In symmetrical loading, weight is evenly distributed across the sagittal or frontal plane; in contrast, asymmetrical loading results in unequal weight distribution across the left/right or anterior/posterior axes of the body. Zhang, reported that under asymmetrical load conditions equivalent to 10% of body weight—such as single-handed carrying, shoulder-loading, or front-holding—older adults exhibited significantly increased cadence and decreased normalized step length (SL) and stride time (ST) [17]. These findings suggest that asymmetrical load carriage adversely affects gait performance in older adults. Gait speed and step length are commonly used indicators of postural stability during linear walking. To improve balance, older adults often adopt a compensatory strategy marked by higher cadence and reduced step length—commonly referred to as a "shuffling gait" [18]. This strategy shortens step length, thereby limiting the displacement of the center of mass, reducing body acceleration, and minimizing ground reaction forces. However, existing evidence suggests that this strategy does not necessarily lower fall risk in older adults. In fact, increased cadence elevates the likelihood of foot-to-foot contact, thereby raising the risk of self-induced tripping [19, 20]. Asymmetrical load carriage introduces torsional forces on the trunk, increasing the demand on the anti-rotational capacity of muscles around the ankle, hip, and other joints in older adults. Additionally, it complicates the biomechanical control required to maintain the center of mass over the base of support [21].

Narouei et al., Bampouras et al., and Badawy et al. (2019) reported no significant effects of symmetrical load carriage on gait parameters [7, 11, 13]. Similarly, Allahverdipour et al. found that symmetrical loading had no significant effect on the time to complete the Timed Up and Go (TUG) test [12]. Previous research

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has demonstrated that bilateral load carriage, compared to unilateral loading, significantly reduces spinal strain, with biomechanical impact estimated to be about half that of single-handed carrying [22]. According to Bampouras et al., symmetrical loading reduced fear of falling in older adults, enhanced perceived walking stability, and may have modulated neural mechanisms involved in postural control [7]. The sensation of "weighted grounding" associated with symmetrical loading was reported to enhance confidence in balance maintenance during quiet standing.

In summary, asymmetrical load carriage impairs gait stability in older adults, as evidenced by increased cadence and decreased step length. Carrying a symmetrical load equivalent to 5% of body weight does not adversely affect gait in older adults and may even enhance postural stability during quiet standing.

Effects of Various Load-Carrying Methods on Joint Kinematics and Muscle Activation During Gait in Older Adults

Matsuo et al. demonstrated that asymmetrical load carriage led to lateral tilting of the trunk and head, unequal shoulder heights, and imbalanced extension torques between the left and right lower limbs [16]. During gait, trunk movement drives upper-limb swinging through shoulder motion, while pelvic rotation initiates lower-limb movement. At this stage, angular momentum is balanced between the upper and lower limbs, contributing to dynamic gait stability [23]. Abnormal trunk and lower-limb movements disrupt angular momentum balance during normal gait. To compensate, other body segments perform compensatory actions, which pose greater challenges for older adults with age-related muscle weakness. In addition to load distribution (symmetrical vs. asymmetrical), some studies also classified load carriage by the load's physical state: stable (e.g., solid objects) versus unstable (e.g., liquids or sand-filled containers). Walsh et al. found that unstable load carriage had a more pronounced impact on trunk stability than stable load conditions [14]. Under unstable load conditions, the Local Divergence Exponent (LDE) in the frontal plane increases, joint angles become irregular, and frontal-plane instability intensifies. Notably, older adults inherently demonstrate lower mechanical stability in the frontal plane compared to the sagittal (anterior–posterior) plane [24–26].

Asymmetrical load carriage leads to imbalanced activation of bilateral muscles, significantly impairing the coordination of homologous muscle groups on both sides of the body. Badawy et al. reported that muscles on the loaded side produced greater force than those on the unloaded side [13]. Among the trunk muscles tested, four showed significantly increased activation under asymmetrical loading: the left external oblique (EO), left lower erector spinae (LES), right latissimus dorsi (LD), and upper erector spinae (UES). The increased activity of these muscles helped maintain an upright trunk posture during gait. Regarding lower-limb muscles, the rectus femoris (RF) showed elevated activation during both posterior load carriage and symmetrical bilateral leg loading. The rectus femoris is a biarticular muscle spanning both the hip and knee joints, primarily responsible for transferring mechanical energy between them (Thiru et al., 1999). This accounts for the increased activation of the rectus femoris under load-carrying conditions. Walsh et al., after evaluating a broader range of lower-limb muscles, reported increased activation of the soleus (SOL) [14]. However, activation levels of the gastrocnemius medialis (GM) and vastus medialis (VM) did not differ significantly between loaded and unloaded conditions. Compared to the GM and VM, the soleus plays a distinct role in gait, contributing more to gravitational support and forward propulsion [27, 28].

In summary, asymmetrical load carriage in older adults induces lateral trunk tilt during walking and causes imbalanced muscle activation between the two sides of the body. Unstable loads increase trunk sway amplitude and compromise postural stability in the frontal plane. Among lower-limb muscles, the rectus femoris (RF) demonstrated the highest level of activation.

Effects of Different Load Weights on Gait Performance in Older Adults

Zhang reported that when older adults carried a unilateral load equivalent to 10% of their body weight, stride time (ST) significantly decreased, while cadence significantly increased compared to unloaded walking [17]. In contrast, Bampouras et al. found that unilateral upper-limb loading using a shopping bag had no significant effect on dynamic gait stability [7]. This suggests that frontal plane perturbations induced by such loading can be compensated for through effective motor control strategies. However, the discrepancy in findings may be attributed to differences in load design: the maximum unilateral load used in the Bampouras et al. study was less than 5% of body weight [7].

Furthermore, Zhang reported that carrying a backpack load equal to 10% of body weight did not significantly alter gait parameters in older adults [17]. In contrast, Walsh et al. found that carrying 15% of body weight on the back increased step width (SW), potentially compromising postural stability [14]. SW is a critical gait parameter for evaluating fall risk in older adults. When older adults are afraid of falling, they tend to increase step width and reduce stride length to enlarge their base of support and limit displacement of the center of mass, thereby improving stability [4]. Similarly, McAndrew et al. found that variations in SW are strongly correlated with gait stability [29]. A wider step width generally enhances dynamic stability during walking by providing a broader base of support, which aids in maintaining balance and reducing fall risk. Carrying a backpack load equal to 10% of body weight did not negatively impact gait stability in older adults. However, when the load increased to 15% of body weight, older adults reported a perceived decline in gait stability. This perceived instability triggered compensatory mechanisms, such as increased step width, to improve postural control during walking.

A cross-study comparison of the included literature indicates that different load magnitudes have distinct impacts on gait parameters in older adults. Unilateral hand-held loads equivalent to 10% of body weight were found to increase cadence and decrease gait cycle duration. Carrying a backpack load amounting to 15% of body weight was associated with increased step width during walking. However, the exact load threshold at which gait alterations occur is influenced by various factors, including sex, physical fitness, and functional capacity. Further experimental research is required to accurately determine this threshold.

Effects of Varying Load Magnitudes on Joint Kinematics and Muscle Activation During Gait in Older Adults

Matsuo et al. reported that increasing asymmetrical load progressively induced lateral tilt of the head and trunk, exacerbated shoulder height asymmetry, increased torque in the contralateral hip joint, and decreased torque in the ipsilateral hip [16]. As external load increases, additional musculoskeletal components are recruited to maintain frontal plane alignment and trunk equilibrium. Moreover, adequate hip abduction torque is essential for stabilizing the supporting lower limb. The trunk and limbs operate synergistically during gait, and their coordination is crucial for maintaining postural stability. Arm swing and trunk rotation dissipate ground reaction forces and enhance gait stability. The trunk and shoulders function as biomechanical dampers during locomotion, playing a critical role in maintaining postural balance. Trunk rotation and sway help reduce gait oscillations and improve dynamic postural stability [30]. Increased loading typically restricts natural arm swing during walking in older adults. The upper limbs assist mediolateral stability by regulating trunk rotation. In the absence of arm swing, postural stability significantly deteriorates, particularly in older adults [31]. The lower limbs and trunk coordinate synergistically to maintain both vertical and mediolateral stability during gait. During the stance and swing phases, they regulate the body's center of mass (CoM), while trunk motion ensures smooth and stable locomotion [32]. Increased loading amplifies the contribution of the trunk and limbs, whose coordinated movements are essential for maintaining postural stability.

As asymmetrical load increases, the body deviates further from its normal gait pattern, as indicated by trunk lean toward the loaded side, decreased hip torque on the ipsilateral side, and increased torque on the contralateral side.

Conclusions

This study systematically reviewed the biomechanical effects of load carriage on gait in older adults and summarized the experimental methodologies employed to assess gait parameters, joint kinematics, and muscle activity. It synthesized findings based on different load types and magnitudes, highlighting their effects on gait stability, joint kinematics, and muscle coordination during walking in older adults. Current evidence indicates that optical motion capture systems are predominantly used to assess gait and joint kinematics, whereas surface electromyography (sEMG) is commonly applied to measure muscle activation. Load carriage compromises gait stability, alters joint kinematics, and disrupts muscle coordination—effects that are especially pronounced under asymmetrical loading conditions.

Study Limitations

Although this study provides a comprehensive review of the biomechanical effects of load carriage on gait in older adults—specifically in terms of gait parameters, joint kinematics, and muscle activity—several limitations should be acknowledged: (1) The number of included studies was relatively small, which limits the generalizability of the findings and necessitates cautious interpretation. (2) Most included studies focused solely on level-ground walking. The biomechanical implications of load carriage under more challenging

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locomotor tasks—such as obstacle crossing or stair negotiation—remain insufficiently studied and warrant further investigation.

Future Research Directions

In view of the biomechanical effects of load carriage on gait in older adults, future research should focus on the following key areas: (1) Investigate the effects of different load magnitudes, while considering individual factors such as sex and physical fitness, to establish safe load thresholds for walking in older adults. (2) Design and assess exercise-based interventions to mitigate the negative impact of load carriage on gait performance and reduce the risk of falls in older adults.

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Research on the Influence of College Physical Education on the Sports Behavior Habits of Female College Students from the Perspective of Emotional Experience

This study investigates how college physical education affects the exercise habits of female students. In response to the global challenge of promoting healthy lifestyles and insufficient exercise participation among female college students, a correlation model was constructed to examine the relationship between emotional experiences and exercise behavior. Using stratified random sampling, 100 sophomore female students enrolled in aerobics courses were selected as research subjects. Emotional experiences and exercise behavior characteristics were assessed through standardized scales, and SPSS 26.0 was used for correlation analysis and regression modeling. Results indicate a significant positive correlation between emotional experience and exercise habits ($r = 0.536$, $p < 0.001$). Emotional variables explain 28.7% of behavioral variation. Prediction is strongest in the Low Emotional Experience Group ($n = 30$, $R^2 = 0.315$), while the High Emotional Experience Group ($n = 12$) exhibits behavioral attenuation after emotional saturation. This study innovatively reveals the gradient attenuation in the emotion–exercise relationship and supports the applicability of the emotion regulation need theory in exercise contexts. It is recommended to construct an emotion-oriented curriculum system to enhance exercise participation through engaging project design, achievement reinforcement, and differentiated intervention strategies. Limitations include the small sample size and the inability to infer causality from the cross-sectional design. Future multicenter longitudinal studies are needed to further explore the underlying mechanisms.

Keywords: emotional experience, physical education teaching in colleges and universities, sports behavior habits, female college students

Introduction

Globally, the promotion of healthy lifestyles has become a key priority for governments and educational institutions. However, the convenience brought by modern technology and the Internet has altered dietary habits, increased life stress, and reduced leisure and exercise time, leading to declining physical activity levels. This reduction negatively impacts health and raises the risk of chronic diseases and physical function deterioration [1]. In addition, foreign studies have also pointed out that there is a phenomenon of insufficient exercise in the lifestyles of college students, but healthy lifestyles can effectively control and improve the physical fitness and BMI of obese adolescents [1]. Physical education courses in colleges and universities play an important role in promoting exercise behavior habits of female college students. The design and teaching methods of physical education courses have an important impact on students' exercise motivation and behavior. For example, providing diverse sports projects, personalized choices, and introducing psychological skills training can effectively improve students' anxiety levels and personal coping resources [2]. In addition, the integration of self-supported teaching styles and mental health education in physical education courses can reduce students' fear and anxiety about failure, thereby promoting their active participation in physical activities [2].

Despite these benefits, female college students in China still face multiple challenges in their exercise behaviors and habits. These issues not only compromise their physical and mental health but also hinder their ability to maintain long-term participation in exercise. First, insufficient exercise time and lack of regularity are common. A survey of ordinary undergraduate universities in Guiyang shows that 42.08% of female college students are mainly busy with their studies during their leisure time, and 35.68% of the students have irregular and unstable time periods for participating in sports activities. This reflects that they have obvious deficiencies in time management, and it is difficult for them to form stable exercise habits [3]. Second, the exercise intensity and frequency of female college students are also generally low. Although a considerable number of students participate in physical exercise, their exercise intensity and frequency are often insufficient to meet the health-promotion standards, and the frequency and time of exercise are still inadequate. Their sports behavior is more out of interest or short-term goals rather than long-term health needs [4]. Third, psychological barriers and emotional distress are also evident. Many students report negative emotions such as apathy, laziness, fear of effort, anxiety, low self-esteem, shyness, and timidity in relation to sports, all of which weaken their motivation and persistence [5]. Moreover, the structure and teaching methods of PE courses do not always align with female students' needs, with some reporting that the content is monotonous and fails to spark interest [6].

In psychology, emotions are typically described as a subjective experience that involves an individual's perception of their own psychological state. They are "intense psychological disturbances that involve behavior, conscious experience, and visceral functions" [7]. The James-Lange theory posits that emotional experiences are the result of bodily reactions [8]. The Self-Determination Theory suggests that human behavioral motivation mainly stems from the fulfillment of three basic psychological needs: autonomy, competence, and relatedness. When these needs are met, individuals are more likely to develop intrinsic motivation and thus be more willing to participate in sports [9]. Moreover, a study by Kelly L. Simonton et al. (2023) also indicates that there is a significant positive correlation between positive emotions (such as enjoyment and pride) and exercise behavior [10]. Positive emotions (such as enjoyment and excitement) are the strongest predictors of exercise behavior, while negative emotions (such as boredom and frustration) are negatively correlated with exercise behavior [11].

Developing healthy exercise behaviors brings multi-dimensional benefits to female college students, supporting physical health, mental well-being, and social adaptability. At the level of physical health, regular physical exercise can effectively enhance cardiopulmonary function, optimize body fat percentage, and body posture [12]. At the same time, rhythmic training such as aerobic exercise can significantly improve female students' physical self-esteem, forming a virtuous cycle in aspects such as muscle strength, flexibility, and weight management [13]. In terms of mental health, physical activities significantly improve emotional states through the stress-release mechanism and reduce negative psychological indicators such as anxiety and hostility. In particular, sports forms such as sports dance and aerobics have special effects on improving sensitivity in interpersonal relationships and paranoid tendencies [14]. Long-term participation can further enhance mental toughness and self–efficacy [12]. On the level of social adaptation, the cooperation and competition mechanisms in team sports can systematically cultivate communication skills and a sense of collective belonging [15], expand social networks, and strengthen social support systems [16]. Therefore, long-term adherence to physical exercise helps to cultivate perseverance, discipline, and teamwork spirit among female college students, and these qualities have far-reaching impacts on their future study, work and life.

Methods and materials

1 Research object

In this study, female sophomore undergraduates who selected the specialized aerobics course in the second semester of the 2023-2024 academic year at Shenyang Normal University were used as the sampling frame, and the stratified random sampling method was employed to select the samples. First, all the students who selected the course were divided into 6 natural teaching classes according to the administrative establishment of the college, forming non-overlapping sampling strata. Then, one class was selected from each stratum according to the principle of simple random sampling. Finally, a total of 100 subjects from 2 complete teaching classes were included. The demographic characteristics of the sample showed that the average age of the subjects was 19.2 ± 0.7 years (ranging from 18.3 to 20.1 years). All the subjects met the status of full-time undergraduates, and the average attendance rate of physical education courses in the previous three semesters was $\geq 85\%$. Before the study was carried out, the research protocol had been reviewed and approved by the Ethics Committee of Shenyang Normal University (Ethics Approval Number: 102772021RT004), ensuring that the research process strictly adhered to ethical guidelines and fully protected the rights and safety of the subjects.

2 Research Methods

2.1 Literature Review Method

To ensure the breadth and depth of the literature, this study selected internationally authoritative English databases and domestic core Chinese databases as the main sources of information. The following keywords were used to conduct searches in both Chinese and English databases: (“emotion” OR “affective response”) AND (“Physical Education” OR “Sports Instruction”) AND (“Exercise Behavior” OR “Physical Activity”). The PRISMA process was adopted to build a literature screening system. Regarding the inclusion criteria, the publication time of the literature was restricted from January 1, 2005, to July 31, 2025, to ensure the research’s cutting—edge nature; the literature type was strictly limited to peer—reviewed academic journal papers; the research subjects must be clearly identified as undergraduate students in regular universities; the research content must involve physical education teaching in universities, emotional/affective experiences of female college students, and exercise behavior/physical activity levels. The exclusion criteria included studies with duplicate publications, non-compliant research subjects, insufficient content relevance, and incomplete data. After the above screening process, a total of 45 pieces of literature met the inclusion criteria of this study and were included in the final systematic analysis. These literatures provide empirical evidence for an in-depth exploration of how physical education teaching in universities can shape the exercise behavior habits of female college students by influencing their emotional experiences.

2.2 Questionnaire Survey Method

This study adopted the standardized questionnaire survey method, targeting full-time female undergraduate students at Shenyang Normal University. It systematically investigated the influencing mechanism of emotional experiences on sports behavior habits in the context of physical education teaching. The data collection tools were selected from authoritative scales in the field of psychology:

The “Induced Emotion Scale” compiled by Professor Zhang Liwei was used to evaluate emotional responses during participation in physical education courses. This scale was constructed based on the two-factor theory of emotion, including a three-dimensional structure of pleasure, arousal, and dominance. After cross-cultural adaptation and modification, the α coefficient reached 0.87 (95% CI: 0.83-0.90), and the confirmatory factor analysis showed a good model fit ($\chi^2/df = 2.14$, CFI = 0.93, RMSEA = 0.05). The “Physical Exercise Habit Scale” by Professor Wang Kun [17] was used to measure the characteristics of extracurricular sports behaviors. This tool integrated the theory of planned behavior and the stage-change model, covering four-dimensional indicators of exercise frequency, intensity, duration, and situational dependence. Empirical tests showed that the α coefficient was 0.83 (95% CI: 0.79 — 0.86), and the confirmatory factor analysis confirmed its structural validity ($\chi^2/df = 1.89$, CFI = 0.91, RMSEA = 0.04).

A total of 100 questionnaires were distributed in the study. After data cleaning, 84 valid questionnaires were recovered, with an effective recovery rate of 84%. The sample data covered the dimensions of emotional responses during participation in physical education courses and the characteristics of extracurricular sports behaviors, providing a quantitative analysis basis for exploring the influence of physical education teaching in colleges on female undergraduate students’ sports behavior habits from the perspective of emotional experiences.

2.3 Mathematical and Statistical Methods

This study adopted a multi-stage statistical analysis strategy to systematically analyze the influencing mechanism of emotional experiences on sports behaviors. The data analysis process was as follows:

First, data pre-processing was carried out on the **SPSS 26.0** platform. The double-entry method was used to ensure the accuracy of the original data. Multiple imputation techniques were used to handle missing values, and box-plot analysis and Z-score standardization were combined to detect outliers, ensuring that the data quality met the requirements of statistical analysis. In the modeling analysis stage, the study followed a progressive analysis logic: First, descriptive statistical analysis was used to summarize the distribution characteristics of variables; then, Spearman’s rank correlation analysis was used to initially explore the association direction and intensity between emotional experiences and various dimensions of sports behaviors; finally, a multivariate linear regression model was constructed to systematically test the independent predictive effect of emotional experiences on sports behaviors. Statistical tests strictly followed the principle of two-sided hypothesis testing, with a significance threshold of $\alpha = 0.05$ set. The standardized β value of the regression coefficient and the coefficient of determination R^2 were reported as effect-size indicators. Through systematic quality control and a progressive modeling strategy, this analysis framework provided a rigorous empirical basis for quantitatively analyzing the psychological mechanism of the influence of emotional experiences on sports behaviors.

Results and Discussion

1 Descriptive Statistical Characteristics of the Scores of Female College Students' Exercise Behavior Habits

Based on 84 valid samples (without missing values), this study conducted a systematic descriptive statistical analysis on the scores of female college students' physical exercise habits (Tab. 1). In terms of central tendency indicators, the sample mean (M) was 62.61 points (standard error SE = 2.23), the median (Md) reached 66.20 points, and the mode (Mo) was concentrated at 84.00 points, forming a subgroup aggregation phenomenon centered on this score. The analysis of the degree of dispersion showed that the standard deviation SD = 20.42 (variance = 416.84), the range spanned 92 points (minimum value 13.00 → maximum value 105.00), and the coefficient of variation CV = 0.33 (> 0.15 threshold), jointly confirming the significant heterogeneity of the group's exercise behavior. The distribution pattern test revealed that the skewness coefficient g_1 = — 0.773 (standard error SE = 0.263). After standardized transformation, Z = — 2.94 (|Z|>1.96, p <.05), indicating that the data distribution showed a significant negative skewness (left-skewed), and 65.5% of the sample scores were higher than the mean. The kurtosis coefficient g_2 = 0.310 (SE = 0.520), and the standardized Z = 0.60 (|Z|<1.96, p >.05), indicating that the distribution pattern had no significant difference from the normal distribution but showed a slightly peaked feature. This result supported the theory of the positive aggregation effect of sports participation. The group with a mode of 84 points had a prominent proportion, and the range from 13 to 105 points verified the hypothesis of the continuous spectrum of exercise behavior (Sallis et al., 2012). The limitation of this study was that potential moderating variables, such as professional background was not included, and future studies need to analyze the sources of variation through stratified analysis.

Table 1

Descriptive Statistical Analysis

	n	M	SD	Skewness (Z)	Kurtosis (Z)	Min	Max	Range
Emotional	84	16.86	17.71	2.05***(7.81)	5.57***(10.70)	-12.00	84.00	96.00
Exercise Habit Score	84	62.61	20.42	-0.77***(-2.94)	0.31(0.60)	13.00	105.00	92.00

***p < 0.001, **p < 0.01 (for skewness and kurtosis Z-values)

2 Analysis of the Three-Level Differentiation and Group Heterogeneity of Female College Students' Emotional Experiences

Based on 84 valid samples (N = 84), this study conducted a systematic descriptive statistical analysis of female college students' emotional experiences in physical education contexts. The results revealed both the overall distribution and heterogeneous structure of their emotional responses (Tab. 1). The total emotional scores demonstrated a wide distribution range (range = 96.00), with the mean value (M = 16.86, SE = 1.93) indicating that the overall emotional experience tended to be above a moderate level. However, the relatively large standard deviation (SD = 17.71) and variance (S^2 = 313.74) suggested significant interindividual differences in emotional responses, exhibiting notable dispersion characteristics.

Using the standard deviation grouping method, emotional experience scores were categorized into low (<12), medium (12-27), and high (>27) emotional experience groups (Tab. 2). The Low Emotional Experience Group (n = 30, M = 2.67, SD = 5.87) exhibited substantial internal variability, indicating that the emotional states within this group were relatively unstable, potentially influenced by factors such as motor competence, body image, or social comparison. The Medium Emotional Group (n = 30, M = 21.33, SD = 2.94) clustered around the theoretical median, reflecting that most students maintained a balanced state of emotional activation and regulation during physical education classes. Although the High Emotional Experience Group (n = 12, M = 31.08, SD = 2.43) had a limited sample size, its small standard deviation indicated relatively consistent and positive emotional experiences, suggesting that physical education teaching significantly enhanced emotional states for some students.

Regarding distributional morphology, the overall emotional scores exhibited pronounced positive skewness (g_1 = 2.05, SE = 0.26) and relatively high kurtosis (g_2 = 5.57, SE = 0.52), indicating a right-tailed, leptokurtic distribution. Most students' emotional scores clustered in the low-to-medium range, while a small number of extremely high scores inflated the overall mean. Both the median (16.00) and mode (18.00) were lower than the mean, further confirming the asymmetric nature of the right-skewed distribution. Percentile analysis revealed that 25% of participants scored below 6.60, 50% below 16.00, and 75% below 21.00,

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thereby outlining the cumulative distribution of emotional experiences. In conclusion, the emotional experiences of female college students in physical education contexts demonstrate marked group heterogeneity and distributional skewness. Furthermore, the small sample size in the high-emotion subgroup may limit the stability of parameter estimates. Subsequent studies should improve the representativeness of this group by expanding the sample size or implementing more stringent grouping criteria.

Table 2

Three-Level Classification of Emotional Experience

Group	n	Mean ± SD	SE	Range
Low Emotional Experience Group	30	2.67 ± 5.87	1.07	-12.00 ~ 9.00
Medium Emotional Experience Group	30	21.33 ± 2.94	0.54	17.00 ~ 27.00
High Emotional Experience Group	12	31.08 ± 2.43	0.70	28.00 ~ 36.00
Skewness is significant (p <.01), with a standardized test statistic Z = -2.74.				

3 There is a Significant Positive Correlation between the Emotional Scores of Female College Students in Physical Education Teaching and Their Exercise Behavior Habits

This study revealed the quantitative correlation pattern between emotional experiences and exercise behavior habits through Pearson's product-moment correlation analysis (Tab. 3). The overall sample analysis (n = 84) showed that there was a significant positive correlation between the emotional experience scores and the exercise habit scores (r = 0.536, p <.001, 95% CI[0.370, 0.661]). The correlation coefficient exceeded the medium-effect-size threshold defined by Cohen (1988) (r > 0.50), indicating that emotional experiences could explain 28.7% of the variation in exercise behavior ($R^2 = 0.287$), reaching the recognized substantial prediction standard in the field of sports psychology ($R^2 > 0.25$; Gould et al., 2017).

The group-by-group analysis further revealed the heterogeneity of the correlation pattern. In the Low Emotional Experience Group (n = 30), there was a significant positive correlation between emotions and exercise habits (r = 0.561, p =.001), and the effect size ($R^2 = 0.315$) was higher than that of the overall sample, supporting the positive—cycle mechanism of "emotion improvement—exercise persistence" in which for every one—standard—deviation increase in emotional scores, the exercise habit scores increased by 0.561 standard deviations. In the Medium Emotional Group (n = 30), no significant correlation was found (r = 0.269, p =.150), and the emotional experience could only explain 7.2% of the variation in exercise habits ($R^2 = 0.072$), suggesting that the coordinated change trend weakened under the medium-emotional state. In the High Emotional Experience Group (n = 12), there was an insignificant negative trend (r = — 0.410, p =.186), which might reflect the exercise burnout effect after emotional saturation, but it was limited by the sample size (statistical power β = 0.23 < 0.80). These results confirmed the core role of the emotion-regulation theory in the Low Emotional Experience Group (M = 2.67), while the weak correlation in the High Emotional Experience Group (M = 31.08) might conform to the inverted-U theory, suggesting that the behavior-promotion effect attenuated after the emotion exceeded the threshold. The analysis results suggested that future studies could expand the sample size of the High Emotional Experience Group to verify the potential non-linear mechanism.

Table 3

Correlation Analysis between Emotional Experience and Exercise Behavior Habits

Group	Variable	M	SD	*n*	*r*	*p*
Total Sample	Emotional Experience. Score	15.17	11.09	84.0	0.536**	<.001
Exercise Habit Score	67.44	16.64				
Low Emotional Experience Group	Emotional Experience. Score	2.67	5.87	30.0	0.561**	.001
Exercise Habit Score	58.03	17.62				
Medium Emotional Experience Group	Emotional Experience Score	21.33	2.94	30.0	0.269	.150
Exercise Habit Score	73.87	13.38				
High Emotional Experience Group	Emotional Experience Score	31.08	2.43	12.0	-0.410	.186
	Exercise Habit Score	75.83	13.04			
**indicates a significant correlation at the 0.01 level (two-tailed)						

4 Prediction of the Heterogeneity of Female College Students' Emotional Experiences and the Stratified Moderating Effect

This study focused on the female college students' group, divided them into low, medium, and high groups according to the level of emotional experience, and used a linear regression model to explore the correlation between emotions and exercise habits. The results showed significant heterogeneity (Tab. 4). In model construction, the "emotional experience group" was used as the predictor variable, and the "physical exercise habit score" was used as the dependent variable. The forced-entry method was used to focus on the main-effect correlation.

This study used a hierarchical linear regression model to systematically examine the predictive effect of emotional states on exercise habits. The results showed that there was significant heterogeneity in the inter-group effects (Fig.). The Low Emotional Experience Group (n = 30) had a significant positive predictive effect on exercise habits ($F(1,28) = 12.866$, $p = 0.001$). The unstandardized regression coefficient $B = 1.683$ (95% CI [0.682, 2.684]) indicated that for every one-point increase in emotional scores, the exercise habit scores increased by 1.683 points. The standardized coefficient $\beta = 0.561$ ($p = 0.001$) suggested a medium-intensity effect (Cohen, 1988), and the model explained 31.5% of the variance ($R^2 = 0.315$). In the Medium Emotional Group (n = 30), the regression model was not significant ($F(1,28) = 2.190$, $p = 0.150$). The emotional experience could only explain 7.3% of the variation in exercise habits ($R^2 = 0.073$). The standardized coefficient $\beta = 0.269$ ($p = 0.150$) suggested a positive trend but lacked statistical reliability. The High Emotional Experience Group (n = 12) showed a negative predictive trend contrary to the theoretical expectation ($B=-2.200$, $\beta=-0.410$), but the overall model was not significant ($F(1,10) = 2.018$, $p = 0.186$), the explanation rate dropped to 16.8% ($R^2 = 0.168$), and it was limited by the sample size (statistical power $1 — \beta = 0.23$). The effect-size gradient analysis showed that the predictive strength of emotional experiences on exercise habits showed a non-linear attenuation feature ($R^2 = 0.315$ in the Low Emotional Experience Group > $R^2 = 0.168$ in the High Emotional Experience Group> $R^2 = 0.073$ in the Medium Emotional Experience Group). This pattern supported the extended explanation of the emotion—regulation demand theory (Thayer, 1989): exercise behavior might play a role as an adaptive emotion—regulation strategy in the low—emotional state ($M = 2.67$, $SD = 5.87$), while the negative trend in the high emotional state ($M = 31.08$, $SD = 2.43$) might be related to the emotional saturation effect (Fredrickson, 2001), that is, the excessive abundance of emotional resources after exceeding a certain threshold might weaken the behavior—driving efficacy. At the practical level, it is recommended to implement differentiated interventions for different emotional groups: strengthen the positive feedback system of "emotion-exercise" for the Low Emotional Experience Group, explore non-emotional driving factors for individuals in the high-emotional state (Ryan & Deci, 2000), and include moderating variables such as environmental cues for the Medium Emotional Group to deepen the mechanism research. The problem of low statistical power caused by the insufficient sample size of the High Emotional Experience Group needs to be improved through stratified sampling and moderating variable analysis in future studies.

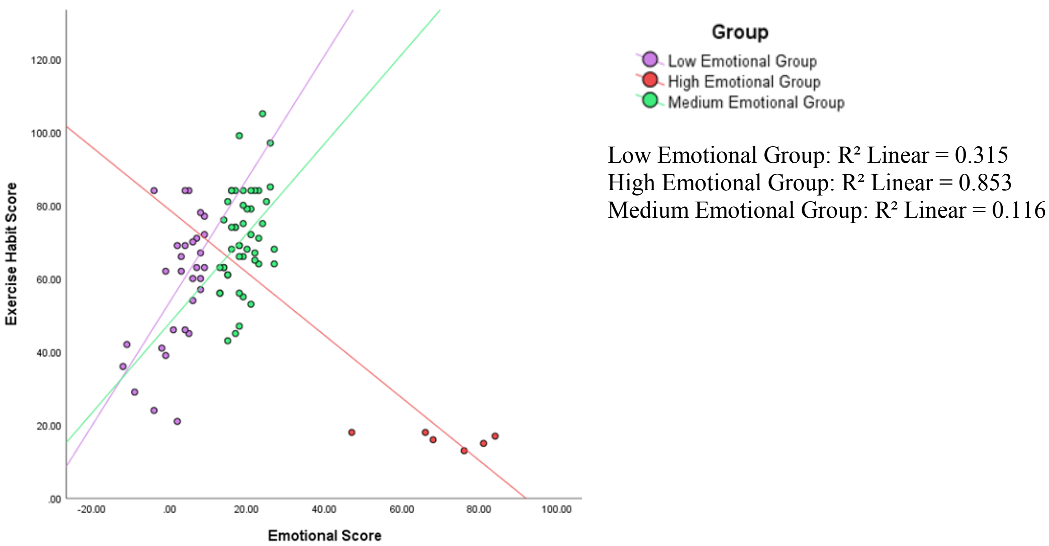

Figure. Exercise Habit Score by Emotional Score by Group

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Table 4

Regression Model Summary for Different Emotional Experience Groups

Group	Predictor Variable	B	SE B	β	t	p	F	df	R²	Δ R²
Overall Sample	(Constant)	55.240	2.622	-	21.067	<.001	33.085***	(1,82)	0.287	0.287
(n=84)	Emotional Score	0.804	0.140	0.536	5.752	<.001				
Low Emotion Group	(Constant)	53.545	2.985	-	17.937	<.001	12.866**	(1,28)	0.315	0.315
(n=30)	Low Emotional Score	1.683	0.469	0.561	3.587	.001				
Medium Emotion Group	(Constant)	47.711	17.838	-	2.675	.012	2.190	(1,28)	0.073	0.072
(n=30)	Medium Emotional Score	1.226	0.829	0.269	1.480	.150				
High Emotion Group	(Constant)	144.225	48.279	-	2.987	.014	2.018	(1,10)	0.168	0.168
(n=12)	High Emotional Score	-2.200	1.549	-0.410	-1.421	.186				
Significance markers: ***p <.001, **p <.01 (Two-tailed test)										

Conclusions

This study systematically examines the heterogeneous mechanisms through which university physical education (PE) influences the exercise habits of female college students, employing a three-tiered analysis of emotional experiences. The analysis reveals distinct patterns across different emotional profiles. For the Low Emotional Experience Group, a significant positive driving effect was observed, robustly validating an "emotional improvement—exercise persistence" cyclical mechanism. Within the university PE context, positive instructional interventions effectively enhance these students' emotional states, which in turn motivates sustained exercise, thereby fostering a virtuous cycle. Conversely, the Medium Emotional Experience Group demonstrated no significant correlation between PE and exercise habits. This lack of association may be influenced by contextual factors, such as the level of peer support, instructor behavior, and physical conditions, including teaching facilities and venue quality, which might supersede the influence of emotional experience. Although limited by a small sample size, the High Emotional Experience Group exhibited an insignificant negative trend. This suggests a potential behavioral decline threshold after a state of emotional saturation is reached. When emotional states are highly positive, excessive emotional stimulation may paradoxically diminish exercise enthusiasm, leading to complacency. For instance, prolonged periods of intense excitement may elevate expectations to a level that subsequent exercise sessions cannot sustain, potentially resulting in boredom and undermining long-term habit formation. These findings provide two key theoretical contributions. First, they offer insights into the applicability of the Emotion Regulation Need Theory in PE settings, illustrating how students' distinct emotional experiences create differential needs for exercise-induced emotional regulation, which directly impacts their behavioral choices. Second, the results provide empirical evidence that supports the extension of the inverted U-shaped hypothesis to exercise contexts. The observed negative trend in the high-experience group aligns with the hypothesis's proposition that a factor's positive relationship with behavior can reverse beyond a certain threshold. From a practical perspective, this study underscores the significant role of emotions in female students' exercise experiences, offering actionable guidance for PE instructors. Teaching methods should be tailored to students' emotional profiles through tiered, precision-targeted interventions. For students with poor exercise moods, instructors should strengthen emotional motivation by setting personalized goals and employing positive feedback mechanisms to foster a sense of accomplishment and boost confidence. For students with moderate to high exercise motivation, the focus should shift to optimizing environmental factors, such as fostering positive peer interactions through cooperative activities, ensuring high-quality facilities, and adjusting instructional difficulty based on students' capabilities.

However, this study has several limitations. First, the small sample size of the High Emotional Experience Group limits the ability to comprehensively examine underlying mechanisms, potentially obscuring the nuanced relationship between intense emotional states and exercise behavior. Second, the geographic distribution of the sample was limited, as participants were drawn exclusively from a few selected institutions. This restricted sampling frame may affect the representativeness of the findings for the broader population of female undergraduates, thereby constraining the generalizability of the results. In light of these limitations, future research should prioritize the expansion of the overall sample size. Particular emphasis should be placed on recruiting a greater number of participants from the High Emotional Experience Group and other distinct subgroups to enhance statistical power and strengthen the robustness of the conclusions. Furthermore, broadening geographic coverage and diversifying institutional types—such as including universities from various regions and different tiers—would improve the external validity of the findings. Finally, employing a longitudinal design to track the evolution of emotional experiences and exercise habits over time could provide deeper insights into their dynamic interplay. This approach would thus enable more precise and forward-looking recommendations for university physical education programs.

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Differentiation of the jump shot technique in handball players of various qualification levels based on kinematic indicators

This study aimed to identify the kinematic and biomechanical differences that occur during the execution of the jump-shot technique in elite and sub-elite male handball players. A total of ten right-handed athletes (five elite and five sub-elite) participated in the study; each player performed four jump shots. Movements were recorded and analyzed using high-speed 3D motion capture, electromechanical sensors, and laser radar technology. Based on the collected data, key kinematic variables such as center-of-mass oscillation and foot-movement distances were analyzed in detail. The findings revealed that vertical movement components and explosive-strength parameters play a critical role in increasing throwing force during the jump shot. The results indicate that greater vertical displacement and optimal coordination of lower-limb actions contribute significantly to throwing efficiency. Considering the biomechanical advantages of the jump-shot technique is essential for individualizing technical training programs and preventing sports injuries. This study highlights the importance of applying biomechanical diagnostics in handball to improve performance and maintain player health.

Keywords: throwing technique, jumping, biomechanics, center of mass, sports kinematics

Introduction

According to the International Handball Federation, more than 30 million athletes currently play team handball in 183 countries. Estimates indicate that handball players perform approximately 48,000 throwing actions during a single season, with an average throwing speed of about 130 kilometers per hour [1]. The overhead throwing technique in handball is considered one of the most important technical movements that directly influence competition outcomes. This movement requires players to direct the ball toward the goal with maximum speed and accuracy [2].

Previous research has reported that fatigue has no significant impact on the execution of throwing techniques in elite handball players throughout an entire match [3]. Kinematic analysis is now regarded as an essential method for gaining a deeper understanding of players' movements and techniques during goal-directed throws. Such analysis allows for a detailed study of the different phases of throwing, including the sequential motion of various body joints [4].

Biomechanical measurements make it possible to conduct an accurate and quantitative analysis of technical elements. This information can serve as a standard within the training process and is an important factor in developing effective training programs. Such an approach is especially valuable for determining an athlete's level of technical proficiency, monitoring individual progress, selecting appropriate kinesiological tools, and modeling methodological processes [5].

During gameplay, conditions are constantly changing. Usually, an opponent stands between the thrower and the goal, which forces the player to perform throws under different and often unstable conditions. As a result, there is considerable variability in both movement execution and throwing effectiveness.

Previous studies have shown that instability created by the opponent during the throwing process can significantly affect throwing kinematics [6]. The maximum velocity of the ball during the throw is generated through a combination of accelerations and decelerations of different body segments and joints [7].

Research by Herbert Wagner and colleagues indicates that as players gain more experience, their ball-throwing speed increases [8]. Recent studies have also shown that the use of various throwing techniques leads to significant differences in ball flight speed [9]. Studies conducted by Chelly and others have demonstrated that the main factors influencing throwing efficiency in handball players are the muscular strength and power of both the upper and lower limbs [10].

The application of innovative technologies to improve goal-shooting techniques is one of the key directions for achieving high performance. For example, analyzing the kinematic indicators of handball players' goal-shooting techniques makes it possible to identify common errors that occur during technical movements and provides opportunities to eliminate them.

Methods and materials

The study was carried out at the SPORTS 360° 3D MA Biomechanics Laboratory of the Uzbekistan State University of Physical Education and Sport. Player movements were recorded and analyzed using STT Technology software with a twelve-camera 3D motion capture system operating at 240 frames per second (Fig. 1).

The STT Full-Body Analysis (19 p) database (2019) was used as reference data. This database, commonly applied in gait analysis, contains seventy-three samples and provides comparative kinematic data such as joint angles, gait cycles, and body movement parameters during specific exercises including walking, running, and lunging.

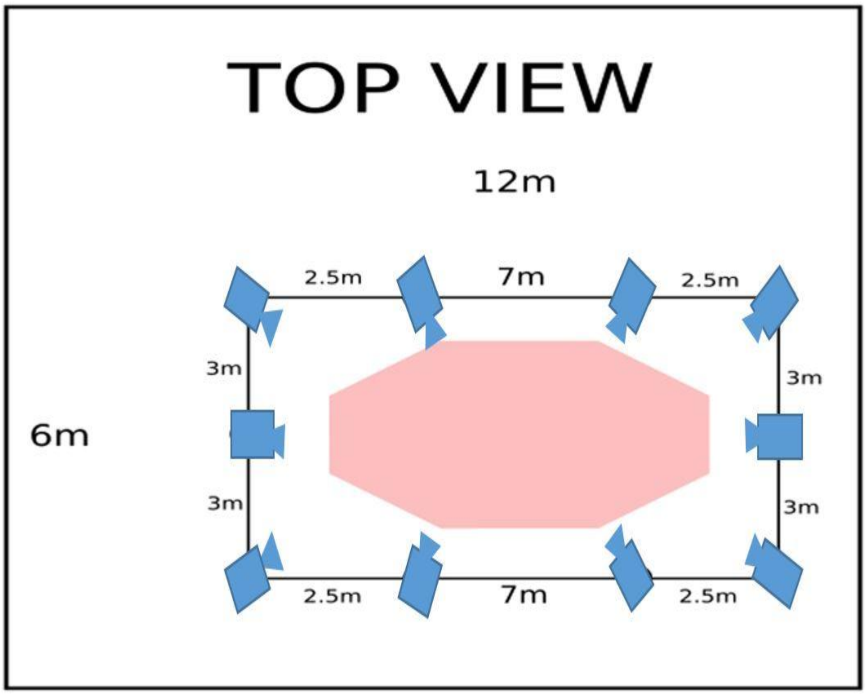

Figure 1. The positioning of 3D cameras in the laboratory setup

Ten right-handed male handball players (n = 10) from the handball team of the Uzbekistan State University of Physical Education and Sport, all participants in the Uzbekistan Higher League, took part in the study. The sample included five elite and five sub-elite athletes. Their mean age was 20.4 ± 4.1 years, mean body weight 74.6 ± 9.49 kg, and mean height 179 ± 8.3 cm. Each participant provided written informed consent before taking part in the research.

Nineteen reflective sensor markers were attached to specific anatomical points on the players' bodies for full-body motion capture (Fig. 2). The experiment was conducted using an IHF size 3 handball, in accordance with the official competition rules of the International Handball Federation. The ball had a circumference of 58–60 cm and a weight of 425–475 g.

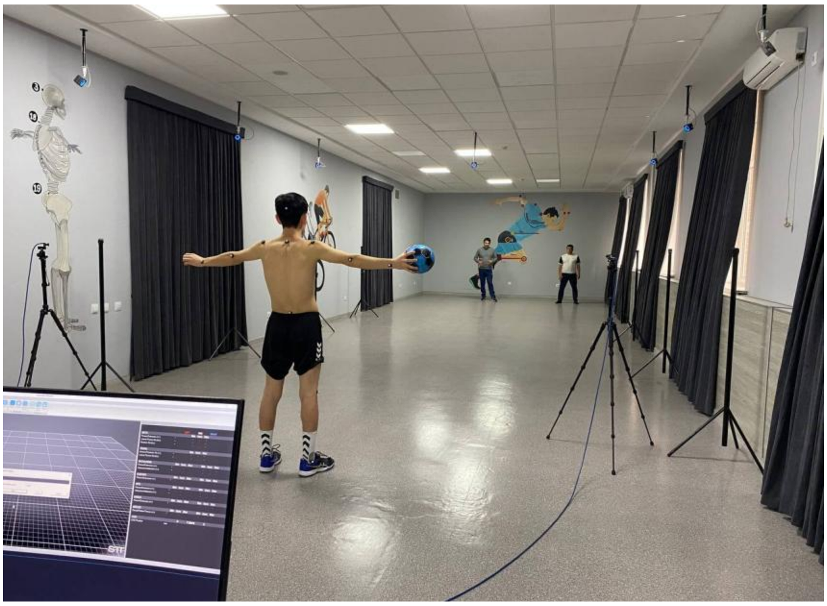

Figure 2. Placement of sensor markers on the body

Results and Discussion

After completing a 20-minute warm-up session, the handball players were instructed on the correct technique for performing the jump shot and were familiarized with the features of the 3D MA laboratory. Each player executed four jump shots from a distance of 8 meters toward the goal. The kinematic indicators associated with the highest ball velocity were selected using the 3D camera system. During the execution of the standing (grounded) shot technique, the full-body kinematic parameters of the players' movements were recorded and analyzed. The kinematic model developed by Katarina Ohnjec, Ljubomir Antekolović, and Igor Gruić served as the basis for analyzing the kinematic indicators obtained in this study.

The primary objective of biomechanical analysis of technical movements is to reveal the mechanisms of movement, explain their underlying causes, and scientifically substantiate the motor actions. This is achieved through the recording of kinematic and dynamic parameters.

T a b l e

Volume indicators of running performed during offensive technical actions by handball players with the title of Master of Sport (n=10)

Parameter	Movement performance indicators of elite handball players	V%	Movement performance indicators of sub-elite handball players	V%
	Value [mm]		Value [mm]	
Vertical COM oscillation	569,80±29,62	5,20	504,42±42,73	8,47
Right braking distance	204,08±21,90	10,70	159,50±19,59	12,28
Left braking distance	166,30±12,81	7,72	128,50±11,84	9,22
Right propulsion distance	340,92±34,86	10,2	275,08±21,98	7,99
Left propulsion distance	369,95±6,94	6,94	307,67±31,04	10,09
Support distance for right contacts	401,80±34,89	8,68	347,67±46,74	13,44
Support distance for left contacts	426,55±17,39	4,08	363,08±30,74	8,47
X coordinate of the right toe during contacts	675,30±44,17	6,54	631,42±44,62	7,07
X coordinate of the left toe during contacts	497.95±57,15	11,48	431,92±37,47	8,67
Speed of the ball m/s	29,10±4,14	14,23	24,75±2,56	10,79

The parameters presented in the above table primarily encompass the vertical and horizontal components of movement. The analysis includes the calculation of the mean values and standard deviations for each parameter.

During the jump shot performed by elite handball players, the mean value of vertical displacement was 569.80 ± 29.62 mm, whereas for sub-elite players it was 504.42 ± 42.73 mm. In modern handball, greater vertical displacement is considered important for enhancing the effectiveness of goal shooting.

Elite players demonstrated a right-foot landing distance of 204.08 ± 21.90 mm, while sub-elite players showed 159.50 ± 19.59 mm. The landing distance provides insight into how athletes regenerate speed and force following a vertical jump. The left-foot landing distance was 166.30 ± 12.81 mm in elite players and 128.50 ± 11.84 mm in sub-elite players.

The average right-foot propulsion distance was 340.92 ± 34.86 mm for elite handball players and 275.08 ± 21.98 mm for sub-elite players. The left-foot propulsion distance measured 369.95 ± 6.94 mm in elite players and 307.67 ± 31.04 mm in sub-elite players. These indicators reflect the athletes' ability to coordinate force application and movement during the throwing action.

During the execution of the throwing technique, elite handball players achieved a ball velocity of 29.10 ± 4.14 m/s, while sub-elite players reached 24.75 ± 2.56 m/s. The throwing motion is biomechanically complex and influenced by the athlete's strength, speed, lower-limb movements, and ability to maintain correct posture during static phases. The synchronization of arm and leg movements during the throw is crucial for achieving maximal ball velocity.

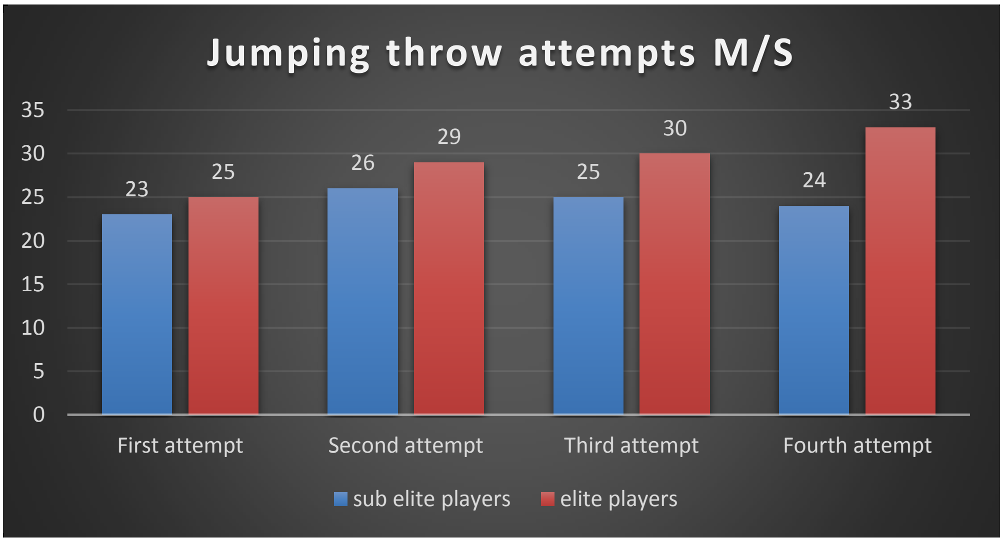

Figure 3. Attempt of a jump shot execution by handball players

In the first attempt, sub-elite handball players performed the throw at a velocity of 23 ± 2 m/s, while elite players achieved a throwing speed of 25 ± 3 m/s. In the second attempt, elite players reached a velocity of 29 ± 5 m/s, whereas sub-elite players recorded a speed of 26 ± 3 m/s (Fig. 3). Van den Tillaar and Ettema have shown that 67 % of ball velocity during a throw depends on the speed of arm extension and shoulder rotation [7]. In order to compare the obtained results, we identified the kinematic indicators of the jump shot technique performed by both elite and sub-elite handball players.

Conclusions

Improving the technical preparation of handball players remains one of the most important challenges in modern sports training. Numerous researchers have proposed different methods and tools to enhance the technical skills of athletes. The use of contemporary technologies plays a crucial role in preventing injuries and improving technical performance.

The present study demonstrates that during the execution of the jump shot, parameters such as foot movement distances, ground contact distances, vertical displacement, and ground contact coordinates have a significant impact on the force, effectiveness, and accuracy of the throw. The findings indicate that the coordination and precision of lower-limb movements, along with overall body stability, are essential for enhancing technical performance.

Therefore, designing training programs based on detailed kinematic indicators allows for a more individualized and scientifically grounded approach to athlete preparation. Such programs can help improve the efficiency of movement patterns, increase throwing power, and reduce the risk of injury. Conducting biomechanical analyses of this type is an important step toward optimizing performance and advancing technical mastery in handball players.

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Effect of "Xuling DingJin" in Tai Chi on Lumbar Spine Biomechanics during Walking

Background: Low back pain is a common condition. The Tai Chi posture of "Xuling Dingjin" may help alleviate lower back pain, but its biomechanical characteristics are not yet fully understood. This study aims to explore the effects of the "Xuling Dingjin" posture on the biomechanics of the lumbar spine during walking, and verify its potential benefits for its application in injury prevention and rehabilitation.

Methods: 12 experienced Tai Chi practitioners participated in the study. The VICON motion capture system, AMTI force measurement platform, and OpenSim software were used to collect lumbar biomechanical data, including activation of the paravertebral muscles and the bending angles of the L4-L5 segment of the lumbar spine.

Results: Walking with "Xuling Dingjin" posture significantly increased the activation levels of all target muscles ($P<0.05$), especially the deep stabilizing muscles (multifidus and longissimus). The forward flexion angle of the L4-L5 segment in the sagittal plane decreased and the trend of asymmetric lateral flexion in the coronal plane was corrected, while there was no significant difference in the bending angle in the horizontal plane.

Conclusion: Maintaining the "Xuling Dingjin" posture during walking may enhances the dynamic stability of the spine and reduces the risk of unilateral overload.

Keywords: Tai Chi, Walking, Lumbar, Biomechanics, Opensim, Muscle activation, Balance control, Xuling Dingjing

Introduction

Low back pain (LBP) is now the leading cause of disability worldwide. According to the World Health Organization (WHO), about 80% of adults will experience at least one episode of LBP during their lifetime [1]. In an aging society, the incidence of lumbar degenerative disorders is rising sharply and the age of onset is becoming younger. This situation highlights the urgent need to develop novel strategies for preventing and treating LBP.

Walking is the most fundamental human activity. During gait, the lumbar spine must absorb ground-reaction forces and dynamic trunk loads; any biomechanical imbalance can disrupt disc pressure distribution and accelerate facet-joint wear. In a normal gait cycle, the lumbar spine flexes, extends, and laterally bends to accommodate shifting body weight. Coordinated contraction of the core muscles—erector spinae, transversus abdominis, and others—is essential for spinal stability. Compared with healthy individuals, people with low back pain show more in-phase coordination between thoracic and lumbar/pelvic motion and exhibit higher activation levels in the lumbar muscles [2]. These findings suggest that altered gait patterns in individuals with low back pain may perpetuate or even exacerbate their symptoms.

A range of treatments exists for low back pain, including pharmacologic and surgical interventions, yet these options are costly and carry inherent risks. In recent years, exercise therapy—particularly Pilates and core-strengthening programs—has gained popularity [3]. Walking, a simple and accessible intervention, has also shown promise; increased walking volume is associated with a reduced risk of developing LBP [4], and randomized trials demonstrate that it lowers pain by improving back-muscle endurance [5]. Mindfulness-based walking has been examined, but mindfulness alone did not yield additional pain relief [6]. Tai-chi research suggests it can elevate pressure-pain thresholds in the lumbar region [7] and may further improve hip range of motion and neuromuscular coordination.

Tai Chi, a traditional Chinese martial art, has been shown to alleviate lumbar strain and prevent lumbar disc herniation [8-9]. The posture "Xuling Dingjin" central to Tai Chi practice, emphasizes spinal elongation and stabilization, thereby enhancing the strength and stability of the lumbar muscles [10]. Biomechanically, this posture treats the spine as a flexible chain: the cervical spine serves as a relatively fixed fulcrum, while the lumbar spine is allowed to extend and undergo sequential adjustment. Such alignment is believed to lengthen the spine and optimize vertebral positioning [11]. However, most studies on the physiological effects of "Xuling Dingjin" remain at the level of subjective experience, and experimental evidence validating its biomechanical benefits is still lacking.

Existing research is largely cross-sectional, with few studies investigating the biomechanical mechanisms of the lumbar spine during walking [12] and none examining the biomechanical impact of the "Xuling Dingjin" posture of Tai Chi on the lumbar spine during gait. Our study aims to determine whether this posture enhances the safety of walking by imposing lower biomechanical demands on the lumbar spine. We hypothesize that (1) "Xuling Dingjin" improves lumbar stability, and (2) maintaining this posture while walking provides a safer mode of locomotion.

Methods and materials

Twelve asymptomatic adults (six males: 41.3 ± 8.8 years, 173.7 ± 5.2 cm, 74.7 ± 8.2 kg; six females: 54.3 ± 3.2 years, 162.2 ± 2.8 cm, 58.3 ± 8.2 kg) with ≥ 5 years of uninterrupted Tai Chi experience were enrolled. Volunteers were excluded if they reported any recent surgical intervention or acute illness, or if their movement execution was deemed inaccurate by a certified Tai Chi instructor. All participants were proficient in the "Xuling Dingjin" stance. Anthropometrics (height, body mass, leg, arm, shoulder, elbow, wrist and ankle breadth) and training history (age, sex, years of practice) were documented prior to data collection. Written informed consent was obtained from each volunteer, and the protocol received approval from the local institutional review board.

The laboratory was equipped with two AMTI force plates (Optima HPS, AMTI, USA) to collect kinetic data at 1000 Hz. Kinematic data were captured at 100 Hz by a Vicon motion-capture system consisting of eight infrared cameras (Vicon V5, Oxford Metrics, UK) and synchronized with the force plates. In accordance with the Vicon Plug-in-Gait full-body marker set, 39 reflective markers were placed on anatomical bony landmarks. Surface electromyographic (sEMG) activity of the multifidus and iliopsoas muscles was recorded at 1 500 Hz using a Noraxon sEMG system (Fig. 1).

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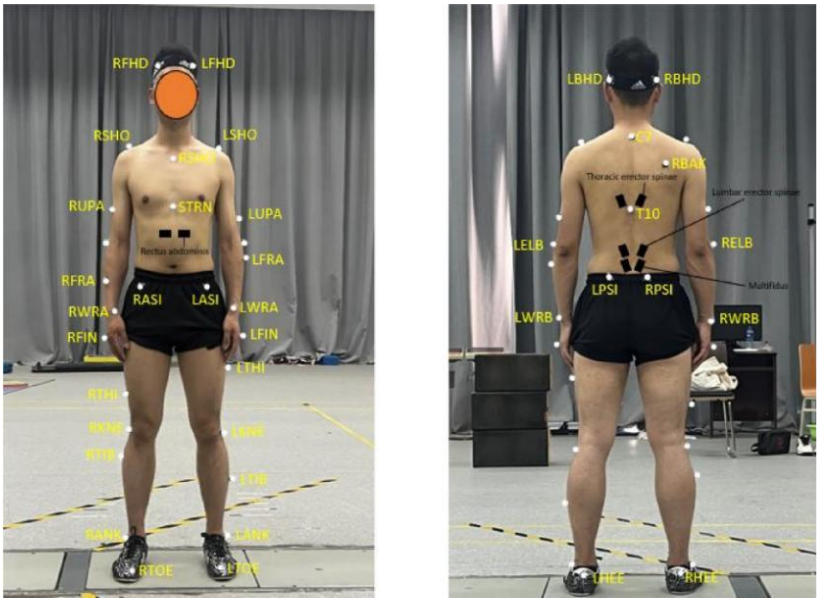

Figure 1. 39 markers on the body joints and surface electromyography locations

Subjects stood at the center of the force plate for static data collection, which was used to build each individual’s VICON model. Dynamic data were then recorded while participants walked along the X-axis (the direction of travel) at a pace controlled by a metronome. They started walking 1.5 meters in front of the force plate and continued until they had walked 1.5 meters past it. A valid gait cycle was defined from the instant the right heel first contacted the plate until the right toe left the plate. Five valid trials were collected for both normal walking and Tai Chi walking.

Paraspinal muscle (PL) activation was obtained via static optimization and time-normalization in OpenSim (v4.4, Stanford University, USA). To validate the OpenSim output, the multifidus was used as an example: raw sEMG signals were first processed with a 10–500 Hz Butterworth band-pass filter and a 50 Hz notch filter, then rectified, normalized, and smoothed with a 50 ms sliding window. Comparison between the sEMG-derived activation and the OpenSim-simulated activation confirmed the reliability of the muscle-activation modelling [13].

L4-L5 angular excursions in flexion/extension (X), lateral bending (Y), and axial rotation (Z) were computed with OpenSim inverse kinematics and subsequently normalized [14].

Results and Discussion

3.1 Muscle activations

In this study, the activation levels of five key lumbar-core muscles—psoas major (PS), multifidus (MF), iliocostalis lumborum (IL), longissimus thoracis (LT), and quadratus lumborum (QL)—were selected as evaluation indices, with activation expressed on a scale from 0 to 1.

In XW, the average activation levels of PS, MF, IL, LT, and QL were all significantly higher than those in normal walking ($P < 0.05$). In XW, the muscle activation curves of IL, LT, and MF all exhibited a biphasic activation pattern during the swing phase, whereas a single-peak activation pattern was observed in W. PS muscle activation under W conditions presented a single peak during the swing phase, whereas under XW conditions it displayed a sustained activation state. QL muscle activation under W conditions peaked in the mid-to-late single-leg stance phase, whereas under XW conditions a triphasic pattern appeared from the swing phase through the single-leg stance phase（Fig. 2) (Tab. 1).

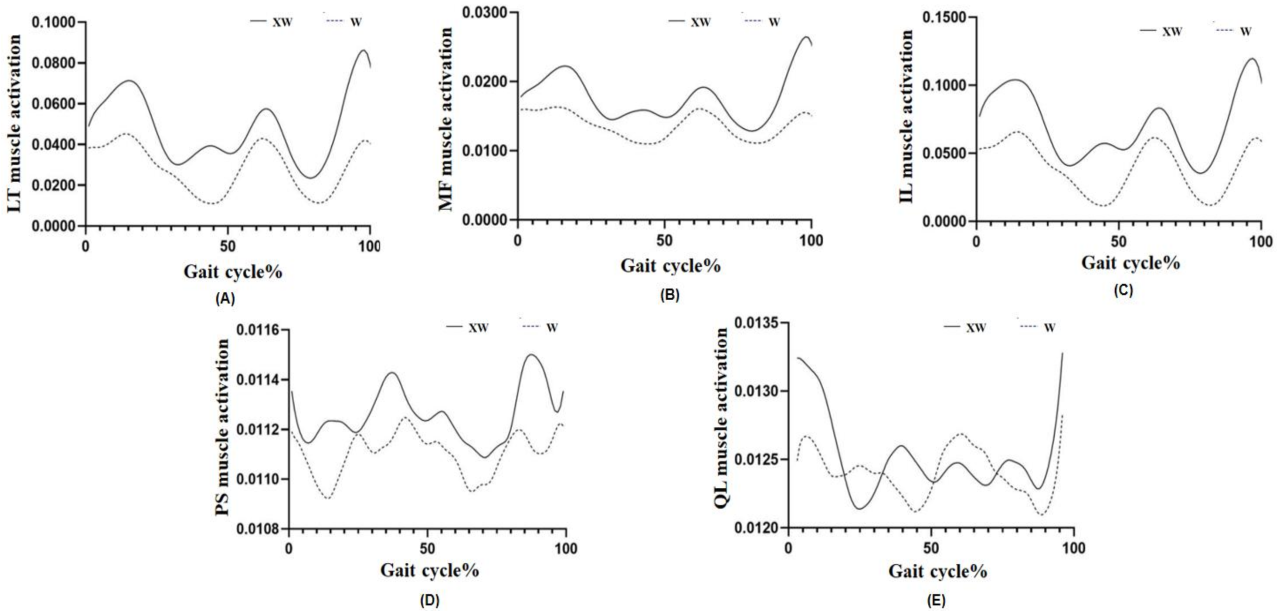

Figure 2. Comparison of muscle activation of the paraspinal muscles
of walking in two conditions.
(A) LT, (B) MF, (C) IL, (D) PS, (E) QL

Table 1

Comparison of average muscle activation of paraspinal muscles in two walking modes

Muscle	Average muscle activation（W）	Average muscle activation（XW）	Z	Z	P	Cohen's d
LT	0.0279（0.0129，0.0415）	0.0423（0.0325，0.0648）	-8.530	-8.530	0.000	1.39
MF	0.0137（0.0118，0.0155）	0.0169（0.0150，0.0198）	-17.418	-17.418	0.000	1.46
IL	0.0399（0.0158，0.0592）	0.0620（0.0483，0.0973）	-8.525	-8.525	0.000	1.47
PS	0.0111（0.0109，0.0113）	0.0112（0.0110，0.0114）	-2.639	-2.639	0.008	1.99
QL	0.0113（0.0110，0.0120）	0.0122（0.0116，0.0129）	-6.253	-6.253	0.000	0.43

3.2 Lumbar Spine Kinematics

In both walking conditions, the mean spinal-curvature angles in the X and Y axes differed significantly ($P < 0.05$); no significant difference was observed in the Z axis. In the X axis, L4–L5 exhibited a biphasic pattern throughout the gait cycle under both conditions. In the Y axis, the neutral spinal position occurred at 50 % of the gait cycle in XW, but earlier in W. In the Z axis, the mean curvature in XW was flatter than in W (Fig. 3) (Tab. 2).

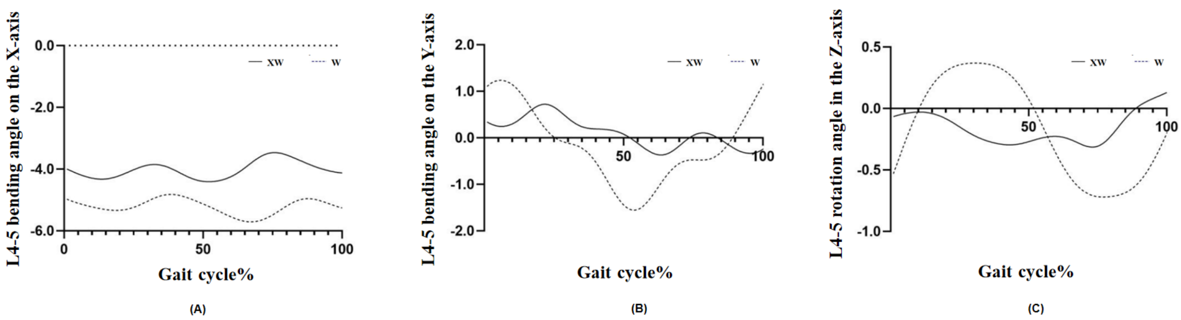

Figure 3. L4-5 motion comparison during XW and W.
(A) Flexion/extension (X-axis), (B) Lateral bending (Y-axis), (C) Axial rotation (Z-axis)

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Table 2

L4-5 motion comparison in X, Y, Z between two walking modes

Axis	Average angle（W）	Average angle（XW）	Z	P
X	-5.1916（-4.9877，-5.3733）	-4.0796（-4.3017，-3.8285）	-8.725	0.000
Y	-0.2015（-0.6455，0.4948）	0.1629（-0.2146，0.2392）	-2.736	0.006
Z	-0.1911（-0.6031，0.2955）	-0.2157（-0.2705，-0.033）	-0.073	0.942

Previous studies on Tai Chi have mostly been limited to intervention studies, with little discussion of its internal mechanisms. In this study, we focused on exploring the most important part of Tai Chi—the state of “Xuling Dingjing”—and quantified its biomechanical effects on the spine. Our results indicate that walking while maintaining this posture improves spinal stability and reduces the risk of injury more than normal walking.

In gait analysis, the activation patterns of core muscles are crucial for understanding how different walking styles influence spinal and pelvic stability. Comparisons between W and XW reveal marked differences in these activation patterns. During normal walking, these muscles typically exhibit a biphasic activation pattern aligned with specific phases of the gait cycle, such as swing and initial heel contact [15-16]. In contrast, the slower, controlled movements and emphasis on stability inherent in XW lead to earlier onset or prolonged activation. LT, essential for maintaining frontal-plane stability and controlling trunk rotation [17], shows higher activation in XW than in W through mechanisms such as extended activation duration and altered neural control strategies [18]. This finding aligns with LT’s established role [19] and with the Tai Chi principle of “moving the body with the waist”. IL and MF display activation patterns similar to LT in XW. Dysfunction of MF has been linked to low-back pain [20]; Tai Chi appears to selectively engage these smaller muscles not typically targeted by other exercises. Under the Tai Chi cue “contain the chest and draw up the back”, IL must isometrically maintain the lumbar lordosis during single-leg stance and, in early swing, coordinate with contralateral abdominal muscles to control axial trunk rotation. Psoas major, pivotal for hip flexion and lumbar stabilization, shows greater activation in single-leg stance during XW, indicating that “Xuling Dingjin” helps maintain spinal balance while standing on one leg. Quadratus lumborum, critical for frontal-plane spinal stability [21], exhibits multiple peaks throughout the XW gait cycle, reflecting sustained activation that minimizes lateral sway and preserves balance. Collectively, these findings demonstrate that XW enhances core-muscle activation and spinal stability, offering therapeutic potential for chronic low-back pain and degenerative spinal disorders. Moreover, Tai Chi’s emphasis on balance and coordination may improve proprioception and reduce fall risk.

During walking, the lumbar spine must continually flex, laterally bend, and rotate in the transverse plane to maintain balance and forward progression; these repeated motions increase anterior disc pressure and predispose unilateral paraspinal muscles to overuse. In contrast, the “Xuling Dingjin” (lightly lifting the crown while keeping the coccyx centered) induces axial elongation of the spine, markedly reducing compensatory lumbar flexion and anterior disc loading—reflected by a significant decrease in L4-L5 sagittal-plane curvature. Muscle activation data show that MF, LT, and other deep stabilizers are significantly more active during XW than during W, aligning with the reduced sagittal motion and demonstrating that “Xuling Dingjin” constrains excessive lumbar movement, allowing the L4-L5 segment to remain closer to a neutral position throughout the gait cycle. This minimizes disc degeneration risk and is particularly relevant for sedentary populations as a daily preventive strategy. In the frontal plane, Tai Chi’s “contain the chest and draw up the back” cue recruits the internal/external obliques and erector spinae symmetrically, correcting the asymmetric lateral trunk lean that typically accompanies alternating lower-limb advancement in normal walking. The resulting balanced activation attenuates uneven compressive loads on lumbar facets and discs, thereby reducing lateral-stress-related falls [22]. In the transverse plane, although L4-L5 axial rotation angles did not differ statistically between XW and X, “Xuling Dingjin” still imposed a subtle constraint on trunk rotation. Excessive lumbar rotation is associated with low-back pain and postural instability. By emphasizing “relax the waist and sink the hips” together with “alternating solid and void”, Tai Chi actively modulates rotational amplitude without adding torsional load to the lumbar spine. Collectively, XW confers clear biomechanical advantages by reducing sagittal-plane loading, correcting frontal-plane asymmetry, and preserving transverse-plane rotational stability, offering a safe and practical exercise strategy for low-back-pain prevention and management.

The small sample size of this study may affect the generalizability of the findings, and future studies will involve groups of different ages, genders, and years of exercise for more reliable statistical analysis. The walking action was chosen to more widely apply the "virtual collar and top strength" movement to daily life, and the research action will be expanded in the future.

Conclusions

Maintaining the "Xuling Dingjin" posture during walking significantly increases both the amplitude and duration of paraspinal muscle activation, thereby enhancing spinal dynamic stability. This postural cue also markedly reduces sagittal-plane flexion and frontal-plane lateral bending at the L4–L5 segment, lowering the risk of unilateral overload. Moreover, no significant change in transverse-plane curvature was observed during Tai Chi-style walking, indicating that it does not add torsional load to the lumbar spine and confirming its safety.

Funding

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Associations of Physical Activity, Sedentary Behavior, and Body Mass Index with Abnormal Posture among Primary School Students: A Cross-sectional Study

This cross-sectional study examined the relationships among physical activity (PA), sedentary behavior (SB), body mass index (BMI), and postural abnormalities in 305 sixth-grade students from urban and rural schools in Shenyang, China. Standardized assessments and mediation analyses were employed. The findings revealed alarming public health concerns, with 84.26% of students showing suspected scoliosis, 51.8% being overweight or obese, and 88.5% engaging in more than two hours of sedentary behavior per day. PA was negatively correlated with both BMI ($r = -0.462$, $p < 0.01$) and postural abnormalities ($r = -0.513$, $p < 0.01$), whereas SB showed positive correlations with BMI ($r = 0.375$, $p < 0.01$) and postural abnormalities ($r = 0.586$, $p < 0.01$). Mediation analysis indicated that PA and SB partially mediated the association between BMI and postural abnormalities. The total effect of BMI (0.059) was partitioned into a direct effect (0.026, 44.07%) and indirect effects through PA (0.015, 25.42%), SB (0.013, 22.03%), and the sequential pathway PA→SB (0.005, 8.48%). These findings suggest that BMI affects postural health not only through direct mechanical loading but also indirectly by reducing PA and increasing SB. The study highlights the urgent need for integrated school-based interventions that promote active lifestyles, reduce sedentary time, and manage body weight to prevent postural abnormalities in children.

Keywords: physical activity, sedentary behavior, body mass index, abnormal body posture, scoliosis, high shoulder, pelvic obliquity, primary school students

Introduction

Abnormal body posture has emerged as a globally prevalent yet frequently overlooked health issue among children and adolescents, with steadily rising prevalence observed in both developed and developing countries over the past decade [1]. Proper posture, defined as the ability to maintain optimal musculoskeletal alignment during both static and dynamic activities, serves as a critical indicator of healthy growth and development [2]. This alignment ensures appropriate biomechanical function, facilitates efficient movement patterns, and prevents premature degenerative changes in joint structures. The developing musculoskeletal system during childhood and adolescence exhibits remarkable plasticity, rendering this developmental period particularly vulnerable to postural deviations while simultaneously offering excellent responsiveness to corrective interventions.

The transformation of modern lifestyles has fundamentally altered physical activity patterns among youth, creating environmental conditions highly conducive to the development of postural problems. Contemporary children encounter an environment characterized by increasingly sedentary behaviors, significantly reduced physical activity levels, and various nutritional challenges that collectively contribute to the rising prevalence of postural abnormalities [3]. Traditional outdoor physical play has been largely replaced by screen-based entertainment, while educational environments have become increasingly sedentary, demanding prolonged sitting with minimal postural variation. Recent epidemiological investigations in China reveal alarming rates of postural abnormalities among youth, with studies indicating that over two-thirds of children and adolescents exhibit multiple postural issues of varying severity [4]. This represents a significant departure from historical norms and underscores the rapidity with which this public health challenge has emerged in rapidly developing regions.

Substantial research evidence has consistently identified physical activity (PA), sedentary behavior (SB), and body mass index (BMI) as key modifiable factors influencing postural development. Longitudinal studies demonstrate that higher PA levels correlate strongly with improved postural outcomes and can serve as a protective factor against the development of abnormalities [5, 6]. Conversely, prolonged sedentary time contributes to gradual spinal misalignment and progressive musculoskeletal deterioration through multiple physiological pathways, including reduced lumbar muscle activity, altered spinal alignment, and connective tissue adaptation [7–9]. The relationship between body weight and postural health demonstrates particular complexity, with elevated BMI identified as a significant risk factor for postural abnormalities. Overweight children show substantially higher prevalence of spinal deviations and musculoskeletal imbalances [10, 11], creating a challenging cycle wherein weight difficulties contribute to postural problems, which in turn further reduce activity levels, thereby exacerbating weight issues.

In today's increasingly competitive educational landscape, students face substantial academic pressures that lead to significantly prolonged study time and corresponding sedentary behavior. The average student now spends between 8–10 hours daily in seated positions for academic activities, creating unprecedented sustained loading on developing spinal structures. Meanwhile, the widespread proliferation of smart electronic devices and the rapid normalization of online learning have further increased screen-based sedentary behavior among students, adding recreational screen time to already extended educational sitting. Under these circumstances, students often unconsciously adopt poor sitting and reclining postures that minimize immediate discomfort at the expense of long-term postural health [7]. Over time, these improper postures become habitual, subtly yet profoundly affecting muscular and joint balance through neurological adaptation and connective tissue remodeling.

The physiological consequences of sustained poor posture are both significant and multifaceted. Prolonged maintenance of improper postures results in uneven joint loading, creating asymmetrical stress distribution across joint surfaces and spinal segments. Contemporary research confirms that low physical activity levels and high BMI represent significant independent and interactive factors in the development of postural abnormalities [8]. The relationship between weight status and postural health appears to follow a U-shaped curve, as both underweight and overweight children demonstrate increased susceptibility to spinal problems compared to normal-weight peers [12], suggesting that optimal postural development requires appropriate nutritional status and body composition.

Postural development is influenced not only by weight status but also by the type and quality of physical activity undertaken. Physical activity patterns demonstrate sport-specific effects, with certain sports like basketball and volleyball associated with increased postural deviations through asymmetrical training loads and repetitive movement patterns, while others like gymnastics promote more symmetrical posture through balanced muscular development [13]. Adolescence represents a critical period for postural development due to rapid growth and hormonal influences, with gender-specific maturation patterns influencing the timing and manifestation of postural issues.

Given the multifactorial nature of postural abnormalities, comprehensive intervention approaches are essential that simultaneously address weight management, physical activity promotion, and sedentary behavior reduction [14]. This integrated understanding represents a significant advancement beyond single-intervention approaches that have demonstrated limited long-term effectiveness. Despite the concerning prevalence of postural issues, substantial grounds for optimism exist, as children and adolescents are in a critical stage of growth and development where postural abnormalities are both preventable and correctable. Early identification and effective intervention during initial stages of abnormality can lead to significant improvement and often complete resolution, particularly when addressing functional rather than structural changes.

This study aims to systematically examine the complex relationships among PA, SB, BMI, and postural abnormalities in school-aged children using comprehensive assessment methods and advanced statistical approaches. By elucidating these relationships and their underlying mechanisms, this research seeks to provide robust evidence for targeted intervention strategies that can be implemented across multiple settings including schools, communities, and healthcare facilities. The ultimate goal is to contribute to the development of effective public health approaches that can reverse current trends and promote optimal postural health for future generations of children and adolescents.

Methods and materials

1 Study Design and Participants

This cross-sectional study was conducted in Shenyang, China to investigate the relationships between physical activity, sedentary behavior, BMI, and postural abnormalities among primary school students. A multi-stage random sampling method was adopted to ensure representativeness. Initially, four primary schools were systematically selected from both urban and rural districts, accounting for socioeconomic and environmental diversity. From these schools, 305 sixth-grade students were included in the final analysis, achieving a high response rate of 94.4%. All participants satisfied predefined inclusion criteria: (1) enrollment in the sixth grade, (2) voluntary participation with informed parental consent, (3) completion of all assessment components, including questionnaires and physical measurements, and (4) absence of physical limitations or medical conditions that could influence posture or physical activity capacity. This rigorous approach ensured the reliability and validity of the study findings.

2 Measures and Procedures

2.1 Literature Review Methodology

This study conducted a comprehensive literature search across multiple academic databases, including CNKI, Wanfang, Web of Science, PubMed, and Chaoxing Qikan. The search utilized key terms and their derivatives related to: (1) primary school students, children and adolescents; (2) BMI, overweight, obesity; (3) physical activity; and (4) body posture. Both Chinese and English search terms were employed. The systematic literature review enabled the collection and synthesis of relevant domestic and international research. This process helped to clarify current developments in the field, define the research direction and framework, and establish the theoretical foundation for this study. Through critical analysis of existing literature, the study identified research gaps and theoretical perspectives that informed the development of the research methodology and analytical approach.

2.2 Physical Activity Assessment

Physical activity was assessed using the Physical Activity Questionnaire for Adolescents (PAQ-A). Although the PAQ-A was originally developed for adolescents (≥12 years), its applicability was verified in our sample of sixth-grade students (approx. 11-12 years) through pilot testing and reliability analysis, which demonstrated good internal consistency (Cronbach's α = 0.82). The instrument includes 9 items assessing activity frequency and intensity over the previous 7 days on a 5-point Likert scale. The total mean score was categorized into low (1-2), moderate (2-3), and high (>3) activity levels for subsequent analysis [11].

2.3 Sedentary Behavior Evaluation

Sedentary behavior was quantified using the Chinese Adolescent Sedentary Activity Questionnaire (ASAQ-CN), a culturally adapted instrument that demonstrates robust psychometric properties in previous validation studies. This comprehensive tool captures time allocation across five conceptually distinct behavioral domains: screen-based activities (television viewing, computer use, tablet/smartphone engagement), cultural pursuits (instrument practice, stationary hobbies, arts and crafts), transportation modalities (motorized travel time), educational activities (homework completion, supplementary classes), and social interactions (seated conversations, telephone communication). The questionnaire comprises 12 specific items that require respondents to estimate time expenditure in hours for each sedentary activity during both weekdays and weekend days. The scoring methodology involves systematic aggregation of reported hours across all items to compute total daily sedentary time. Particular attention was devoted to training research assistants in standardized administration procedures to minimize recall bias and enhance data accuracy. Participants received detailed instructions with concrete examples to facilitate accurate estimation of time allocation. The instrument's established reliability and validity in previous epidemiological investigations [15] supports its appropriateness for the current study's objectives, providing a comprehensive assessment of sedentary behavior patterns beyond simple screen time metrics.

2.4 Postural Measurements

Postural abnormalities were assessed according to the standardized protocols specified in the national standard “Testing Indicators and Methods for Postural Abnormalities in Children and Adolescents” (2022). The assessment included three key indicators: shoulder asymmetry (measured as bilateral difference in acromion height), pelvic tilt (assessed by height differential of anterior superior iliac spines), and spinal curvature (evaluated using Adams forward bending test with a scoliometer). All evaluators received standardized training prior to data collection. Test-retest reliability was examined with 50 participants at a one-week interval, showing high reproducibility across all measures (all reliability coefficients $R \geq 0.829$, $p < 0.001$),

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with an overall mean reliability of R = 0.861 (see Table 1 for detailed reliability statistics). These results support the consistency of the postural assessment protocol and justify the use of initial measurements in subsequent analyses [16].

2.5 Anthropometric Data

Anthropometric measurements were obtained following standardized protocols using carefully calibrated instruments to ensure data precision. Height was measured to the nearest 0.1 centimeter using a portable stadiometer (Seca 213, Germany), with participants standing barefoot in the Frankfurt horizontal plane position. Weight was assessed to the nearest 0.1 kilogram using a digital scale (TANITA HD-390, Japan), with participants wearing lightweight clothing and removing shoes and heavy accessories. All measurements were conducted in duplicate, and average values were used for analysis. If the two measurements differed by more than 0.5 cm for height or 0.5 kg for weight, a third measurement was obtained. Body mass index (BMI) was calculated using the standard formula: weight in kilograms divided by height in meters squared (kg/m^2). The measurement environment was controlled for consistency, with all assessments conducted in private, well-lit rooms at participating schools. Research staff underwent standardized training to ensure uniform measurement techniques and minimize inter-observer variability, following established anthropometric measurement guidelines.

2.6 Statistical Analysis

Data were analyzed using SPSS 22.0. Descriptive statistics were used to summarize sample characteristics, and independent samples t-tests along with chi-square tests were conducted to examine differences between groups. Pearson correlation analysis was applied to assess bivariate relationships among key variables, with the significance level set at $p < 0.05$. To further investigate the underlying mechanism, a hierarchical regression analysis was performed using Model 6 of the PROCESS macro, which allows testing of sequential mediation pathways. This model was specifically chosen to examine the chain mediation effect of physical activity and sedentary time in the relationship between BMI and postural abnormalities, while controlling for gender and geographical origin.

Results and Discussion

This study provides a comprehensive analysis of the interrelationships between modifiable lifestyle factors and postural health in school-aged children. The findings reveal a complex network of associations that underscore the multifactorial nature of musculoskeletal development during this critical growth period. Our results demonstrate significant correlations between physical activity (PA), sedentary behavior (SB), body mass index (BMI), and various postural abnormalities, with important implications for clinical practice and public health interventions.

1 The Multifaceted Protective Effects of Physical Activity

The strong negative correlation between PA and postural abnormalities ($r = -0.513$, $p < 0.01$) highlights the crucial role of regular exercise in promoting musculoskeletal health. This relationship can be understood through several interconnected mechanisms. First, PA contributes to the development of adequate muscle strength and endurance, particularly in the core stabilizer muscles including the transversus abdominis, multifidus, and oblique muscles. These muscles form a natural “corset” that provides essential dynamic stabilization for the spine during both static postures and movement activities [4, 5]. The strengthening of these muscular supports helps maintain proper spinal alignment and reduces the load on passive spinal structures.

Second, PA enhances neuromuscular control and proprioceptive acuity through continuous feedback mechanisms between muscle spindles, joint receptors, and the central nervous system. This improved sensorimotor integration enables more precise postural adjustments and promotes better body awareness, allowing children to self-correct their posture before significant deviations occur [5]. The variety of movement patterns experienced during different physical activities also plays a vital role in preventing the development of muscular imbalances that often underlie postural abnormalities.

The differential protective effects of PA across various postural measures deserve particular attention. PA showed the strongest negative correlation with spinal curvature ($r = -0.308$), suggesting that activities involving multi-directional movements, such as swimming, gymnastics, and team sports, may be especially beneficial for maintaining spinal health. These activities promote symmetrical development of paraspinal muscles and encourage full range of motion in all spinal planes. The correlation with uneven shoulders ($r = -0.351$) indicates that upper body exercises and activities promoting scapular stability might be particularly important for preventing shoulder asymmetries.

2 The Compounding Risks of Sedentary Behavior

The robust positive correlation between SB and postural abnormalities ($r = 0.586$, $p < 0.01$) represents a significant public health concern, especially considering that 88.52% of participants exceeded recommended SB limits. The biomechanical consequences of prolonged sitting are particularly detrimental to developing musculoskeletal systems. When children maintain flexed spinal positions for extended periods during electronic device use or studying, their spinal structures experience sustained asymmetric loading. This can lead to viscoelastic "creep" in intervertebral discs and spinal ligaments, reducing their ability to maintain proper alignment and absorb physiological loads [17, 18].

The varying strength of correlations between SB and different postural abnormalities provides insights into specific risk patterns. The strong association with uneven shoulders ($r = 0.440$) suggests that screen-based activities often involve asymmetrical postures, such as tilting the head to hold a phone or leaning to one side while watching television. These habitual positions can lead to muscular imbalances between the dominant and non-dominant sides, particularly affecting the upper trapezius and levator scapulae muscles. The relatively weaker correlation with pelvic tilt ($r = 0.166$) indicates that this particular abnormality may be more influenced by other factors, such as sitting surface characteristics, chair height, and lower body muscle flexibility.

The timing and pattern of SB also merit consideration. Our finding that weekend SB was significantly higher than weekday SB suggests that unstructured leisure time presents particular risks for postural health. This pattern highlights the importance of addressing recreational screen time and promoting active alternatives during non-school hours. The accumulation of SB throughout the day appears to have cumulative effects on postural muscles, leading to fatigue and reduced capacity to maintain proper alignment.

3 BMI as a Mechanical and Behavioral Mediator

The positive correlation between BMI and postural abnormalities ($r = 0.484$, $p < 0.01$) supports the mechanical loading hypothesis, wherein excess body mass increases stress on developing musculoskeletal structures. The anterior distribution of adipose tissue characteristic of childhood obesity displaces the center of gravity forward, necessitating compensatory postural adjustments including increased lumbar lordosis, anterior pelvic tilt, and forward head posture [19]. These adaptations represent the body's attempt to maintain balance but create abnormal loading patterns that can lead to structural changes over time.

Beyond purely mechanical effects, higher BMI appears to influence posture through multiple indirect pathways. Children with obesity often demonstrate different movement patterns and may avoid certain physical activities due to decreased fitness levels, discomfort during movement, or social factors. This reduced participation in varied physical activities limits opportunities for developing adequate muscle strength, coordination, and proprioceptive skills—all essential components of good postural control [20-21]. Additionally, excess adipose tissue can physically limit joint range of motion and alter normal movement mechanics, further contributing to postural adaptations.

The relationship between BMI and specific postural measures reveals important patterns. The correlation with spinal curvature ($r = 0.313$) suggests that excess weight particularly affects the spine's ability to maintain its natural curves, while the association with pelvic tilt ($r = 0.207$) indicates effects on pelvic positioning and lower body alignment. These findings emphasize the importance of weight management as part of a comprehensive approach to postural health.

4 The Interconnected Risk Triad and Clinical Implications

The intercorrelations among PA, SB, and BMI reveal a self-reinforcing risk triad that creates a complex challenge for intervention strategies. The negative correlation between PA and both SB ($r = -0.363$, $p < 0.01$) and BMI ($r = -0.462$, $p < 0.01$), combined with the positive correlation between SB and BMI ($r = 0.375$, $p < 0.01$), suggests that these factors operate synergistically rather than in isolation. This network effect has crucial implications for clinical practice and intervention design.

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From a clinical perspective, assessment of children with postural abnormalities should include comprehensive evaluation of all three lifestyle factors. The differential strength of associations across various postural measures suggests that targeted intervention approaches may be most effective. For children presenting with spinal curvature issues, exercise programs incorporating multi-planar movements, core stabilization, and activities that promote spinal extension may be particularly beneficial. For those with uneven shoulders, interventions should focus not only on strengthening exercises for the upper back and scapular stabilizers but also on modifying specific sedentary behaviors and workstation ergonomics.

The relatively weaker association between studied factors and pelvic tilt indicates that this particular abnormality may be influenced by other determinants not measured in this study, such as congenital factors, leg length discrepancies, or specific musculoskeletal conditions. This finding highlights the need for thorough individual assessment when addressing pelvic alignment issues.

Table 1

Correlation Analysis of Physical Activity, Sedentary Behavior, BMI, and Postural Abnormalities

Variable	1	2	3	4	5	6	7
BMI	1						
Physical Activity	-.462**	1					
Sedentary Time	.375**	-.363**	1				
Postural Abnormalities	.484**	-.513**	.586**	1			
Uneven Shoulders	.320**	-.351**	.440**	.675**	1		
Pelvic Tilt	.207**	-.236**	.166**	.412**	-0.003	1	
Pinal Curvature	.313**	-.308**	.401**	.650**	.171**	-.146*	1
Note. **Correlation is significant at the 0.01 level (2-tailed); *Correlation is significant at the 0.05 level (2-tailed).							

5 Mediating Effects of Physical Activity and Sedentary Behavior between BMI and Postural Abnormalities

This study established a mediation model to examine whether physical activity (PA) and sedentary behavior (SB) mediate the relationship between BMI and postural abnormalities in elementary school students, controlling for gender and geographical origin (Fig.). The findings revealed a well-defined path structure: BMI not only directly and positively predicted postural abnormalities ($B = 0.059$, $p < 0.001$) but also exerted influence through three distinct indirect pathways. These include the independent mediating pathway of PA ($B = -0.095 \rightarrow B = -0.154$), the independent mediating pathway of SB ($B = 0.079 \rightarrow B = 0.162$), and the chain mediating pathway of PA → SB ($B = -0.095 \rightarrow B = -0.321 \rightarrow B = 0.162$) (Tab. 2). The persistent significance of BMI's direct predictive effect after incorporating the mediators indicates that PA and SB partially mediate the relationship between BMI and postural abnormalities.

The identified mechanism suggests that BMI influences postural outcomes through multiple channels. Beyond the direct mechanical loading effect, higher BMI indirectly contributes to postural abnormalities by reducing physical activity levels and increasing sedentary time. Specifically, students with elevated BMI tend to participate less in physical activities, and lower PA levels are associated with increased sedentary behavior. Both behavioral patterns independently and synergistically elevate the risk of developing postural abnormalities.

These results underscore the importance of implementing comprehensive intervention strategies for postural abnormalities in elementary school students. Effective approaches should simultaneously address weight management, promote physical activity, and reduce sedentary time. Breaking the observed vicious cycle of "high BMI → low physical activity → high sedentary behavior → postural abnormalities" will contribute to more effective prevention and improvement of postural health in this population.

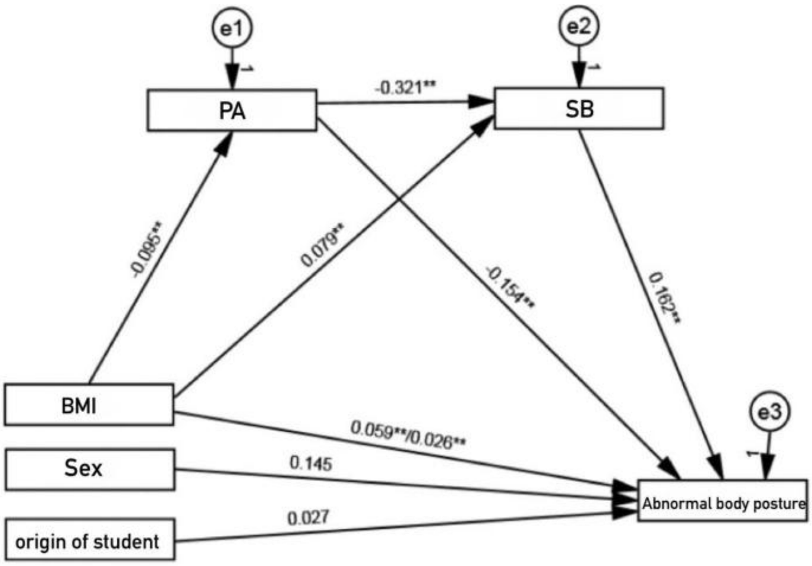

Figure. The Mediating Effect of Physical Activity and Sedentary Behavior on the Relationship Between BMI and Abnormal Body Posture

6 Analysis of the Mediating Effects of Physical Activity and Sedentary Behavior on the Relationship between BMI and Postural Abnormalities

The established chain mediation model reveals a complex network of physiological and behavioral pathways through which BMI influences postural health. The identified pathways demonstrate that the relationship extends beyond simple mechanical loading to encompass intricate behavioral adaptations. The strong negative association between BMI and physical activity (β = -0.413) suggests that increased body mass may create biomechanical constraints that reduce movement efficiency and comfort, thereby discouraging physical activity participation (Tab. 2). This is particularly relevant during the elementary school years when children are developing fundamental movement skills and activity habits. The mediating role of physical activity can be understood through multiple physiological mechanisms. Regular physical activity enhances core muscular strength, particularly in the transversus abdominis, multifidus, and oblique muscles, which provide essential dynamic stabilization for spinal structures. Furthermore, physical activity improves neuromuscular control and proprioceptive acuity through continuous feedback mechanisms between muscle spindles and the central nervous system, enabling more precise postural adjustments and promoting better body awareness.

The positive predictive relationship between BMI and sedentary behavior (β = 0.234) underscores the bidirectional nature of this association. Children with higher BMI may experience increased discomfort during physical activities, leading to greater preference for sedentary pursuits. Simultaneously, prolonged sedentary time contributes to weight gain through reduced energy expenditure, creating a self-perpetuating cycle. The significant positive association between sedentary behavior and postural abnormalities (β = 0.403) can be attributed to the biomechanical consequences of sustained flexed spinal positions during electronic device use and studying, which can lead to viscoelastic “creep” in spinal structures. Notably, the differential effects across various sedentary behavior domains provide insights for targeted interventions. Screen-based activities demonstrated the strongest association with postural abnormalities, particularly affecting shoulder symmetry, while educational sedentary behaviors showed comparatively weaker associations. This pattern suggests that the context and nature of sedentary activities may moderate their impact on postural health.

The quantified mediation effects (PA: 0.015; SB: 0.013; chain: 0.005) provide empirical evidence for developing targeted interventions. The findings suggest that multi-component approaches addressing both weight management and behavioral modifications may yield superior outcomes compared to single-focus interventions. Specifically, programs should aim to break the observed cycle by simultaneously promoting physical activity, reducing recreational screen time, and implementing ergonomic adjustments in school and home environments. For children presenting with postural abnormalities, assessment should include comprehensive evaluation of physical activity patterns, sedentary behaviors, and body composition. The identified pathways suggest that interventions focusing on fundamental movement skill development may be particularly beneficial, as improved motor competence may enhance physical activity participation while reducing

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sedentary time. Additionally, the strong association between weekend sedentary behavior and postural abnormalities highlights the importance of addressing leisure-time activities beyond the school setting.

Table 2

Total Indirect Effects and Mediation Effect Decomposition

Effect Type	Pathway	Effect Size	BootSE	BootLLCI	BootULCI	Propoetio
Direct Effect	BMI⇒Postural Abnormalities	0.026	0.007	0.013	0.040	44.068%
Indirect Effect	BMI⇒PA⇒Postural Abnormalities	0.015	0.004	0.007	0.024	25.424%
	BMI⇒SB⇒Postural Abnormalities	0.013	0.005	0.004	0.023	22.034%
	BMI⇒PA⇒SB⇒Postural Abnormalities	0.005	0.002	0.002	0.009	8.475%
Total Effect	BMI⇒Postural Abnormalities	0.059	0.007	0.045	0.073	

Note. Boot LLCI = lower limit of the 95% confidence interval; Boot ULCI = upper limit of the 95% confidence interval; PA = Physical Activity; SB = Sedentary Behavior. All mediation pathways were tested using bootstrap sampling (n = 5000).

7 Limitations and Future Research Directions

Several limitations of the current study should be acknowledged. The cross-sectional design precludes establishment of causal relationships, and the use of self-reported measures for PA and SB introduces potential recall and social desirability biases. Furthermore, our assessment did not account for several potentially influential confounders, including nutritional status, sleep quality, psychosocial factors, or detailed ergonomic conditions in home and school environments.

Future research should address these limitations through longitudinal designs to establish temporal precedence and better understand the developmental trajectory of these relationships. Incorporation of objective activity monitoring using accelerometers and inclinometers would provide more precise data on activity intensities, patterns, and sitting postures. Investigation of the specific types and contexts of SB most detrimental to postural health would help refine intervention targets. Additionally, research exploring the role of other potential mediators such as muscular endurance, flexibility, and movement competence would provide a more comprehensive understanding of the factors influencing postural health.

Intervention studies testing integrated approaches that simultaneously address PA, SB, and BMI are needed to establish evidence-based guidelines for comprehensive postural health promotion. Such studies should examine not only the efficacy of these interventions but also their implementation in real-world settings such as schools and communities.

Conclusions

This study provides empirical evidence that physical activity (PA), sedentary behavior (SB), and body mass index (BMI) form an interrelated system that jointly influences postural health among school-aged children. The findings clarify the chain mediating effects of PA and SB in the BMI–posture relationship, advancing current understanding of the multifactorial mechanisms underlying postural abnormalities.

The results underscore the importance of integrated rather than single-factor approaches to posture management. Comprehensive strategies should simultaneously promote active lifestyles, reduce sedentary time, and maintain healthy body composition. Schools represent a key platform for implementing such interventions through regular movement breaks, ergonomic classroom designs, and posture education embedded in the curriculum. Family engagement is equally critical, with parents encouraged to model active behavior, set reasonable screen-time limits, and create activity-friendly home environments. Community-level programs offering structured weekend activities can further mitigate sedentary tendencies during leisure time.

Nevertheless, the cross-sectional design restricts causal interpretation. Future longitudinal and interventional studies are needed to validate these pathways and examine long-term outcomes of integrated posture-promoting programs. By emphasizing behavioral and environmental modification during this critical developmental stage, the study provides valuable evidence for multi-level public health strategies to foster healthy postural development among children and adolescents.

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