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Article

The application and effect assessment of biomechanics in English writing instruction

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Abstract: This study aims to investigate the application and effectiveness assessment of biomechanical principles in English writing instruction. The research selected 200 students from a key secondary school as subjects, who were divided into experimental and control groups of 100 students each using stratified random sampling. The intervention period lasted 8 weeks, followed by a 4-week follow-up. A multidimensional evaluation system was established, incorporating biomechanical parameters (35%), learning outcomes (40%), and comfort levels (25%). Data collection and analysis were conducted using OptiTrack motion capture systems, surface electromyography, and pressure sensor array systems. Results indicated that the experimental group's overall writing quality scores improved from 72.3 ± 4.5 to 90.6 ± 3.8, with an improvement rate (25.3%) significantly higher than the control group (9.3%). The incidence of poor posture decreased from 45.6% to 12.3%, while the duration of standard posture maintenance increased from an average of 25 min to 42 min. Regarding age differences, the junior high school group demonstrated better postural adaptability (improvement rate 42.5 ± 4.2%), while the senior high school group showed superior writing stability (coefficient of variation 12.3 ± 1.5%). The study confirms the positive role of biomechanics in English writing instruction, providing scientific evidence and practical references for improving English writing pedagogy. Additionally, the developed evaluation system offers new methodological support for related research.

Keywords: biomechanics; English writing instruction; posture assessment; teaching effectiveness; multidimensional evaluation

1. Introduction

Recent years have witnessed the increasing application of biomechanics in education, particularly demonstrating unique value and potential in language education. The integration of biomechanical principles with educational practices has brought innovative breakthroughs to traditional language teaching methods. Wang [1] demonstrated that the application of biomechanics in education not only optimizes teaching processes but also significantly enhances learning outcomes. In language education, the application of biomechanics originated from phonetics teaching and pronunciation training, where researchers discovered a close relationship between the biomechanical characteristics of human vocal organs and the quality of phonetic expression. As research deepened, the scope of biomechanical applications in language education gradually expanded to writing instruction. Hao et al. [2] proposed motion technical biomechanical characteristic testing methods that provided scientific assessment tools for language teaching, enabling teachers to accurately grasp students' movement essentials. Meanwhile, Niu [3] developed a biomechanics-based posture management system that further enriched teaching methods and provided technical support for standardized instruction.

Writing biomechanics plays an irreplaceable role in English writing acquisition. Liu and Xu [4] demonstrated that biomechanical information collection technology can precisely capture learners' writing motion characteristics, including key parameters such as pen pressure, pen grip posture, and wrist angle. The scientific control of these parameters directly affects writing fluency and sustainability. Feng [5] proposed the force-chemical-biological coupling biomechanical theory, providing theoretical support for understanding the biomechanical mechanisms in writing processes and revealing the complex relationships among muscle strength, joint movement, and neural coordination. From an international research perspective, Wang et al. [6] developed flexible biomechanical energy collection technology that provided new technical means for precise monitoring of writing movements, enabling real-time recording and analysis of various biomechanical indicators during writing. Rivaroli et al. [7] confirmed the important role of biomechanical assessment in movement standardization, providing strong support for the scientific approach to writing instruction.

Current English writing instruction faces multiple challenges. First, traditional writing teaching methods often lack scientific biomechanical foundations, leading to widespread problems such as improper writing postures and hand fatigue among students. Li [8] pointed out that scientific biomechanical simulation technology can help students establish correct writing habits and prevent various problems caused by improper posture. Second, existing teaching assessment methods are relatively singular and struggle to accurately evaluate students' writing behavior and progress. The biomechanical interaction system developed by Jing et al. [9] provided new insights for solving this problem through real-time data collection and analysis for objective assessment of students' writing performance. Additionally, Kumar and Bhowmik [10]showed that the lack of personalized teaching programs is also a significant current challenge, as different students exhibit considerable variations in biomechanical characteristics requiring targeted guidance.

From a practical teaching perspective, the application of biomechanics in English writing instruction still faces challenges such as high equipment costs, operational complexity, and insufficient teacher expertise. Xiao et al. [11] indicated that the promotion of biomechanical assessment technology requires a supporting teacher training system. Tian et al. [12] emphasized the importance of simplifying operational procedures and lowering application barriers. Shahiri et al.'s [13] research on dynamic interactions further revealed the complexity of the writing process, suggesting the need for a more comprehensive evaluation system.

Based on this background, this study aims to explore the application value and effectiveness of biomechanics in English writing instruction. Specific research objectives include: (1) constructing an English writing teaching model based on biomechanical principles, integrating the latest research findings to form a systematic teaching program; (2) developing a scientific writing posture assessment system through real-time monitoring of biomechanical parameters to provide data support for teaching; (3) validating teaching effectiveness and proposing optimization suggestions to provide practical evidence for promotional applications.

Fan and Yang's [14] development of biomechanical probe technology provides technical support for addressing these questions, enabling deeper understanding of biomechanical changes during writing. Yan et al.'s [15] findings in micro-nano devices also offer new possibilities for precise assessment, contributing to the development of more convenient and accurate evaluation tools. Meanwhile, Jing and Tian's [16] discoveries in biomechanical application research provide references for optimizing teaching equipment design. Through this research, we hope to provide new theoretical perspectives and practical methods for English writing instruction, promoting improvements in teaching quality. The study will employ experimental and control groups to verify the effectiveness of biomechanical applications through comparative analysis. The finite element analysis method proposed by Guo et al. [17] will be used for data processing and result validation to ensure the scientific validity and reliability of research conclusions. Furthermore, this study will explore the influence of factors such as age and gender on teaching effectiveness, providing a basis for developing personalized teaching strategies. The research results will not only provide new methods and tools for English writing instruction but also offer valuable references for biomechanical applications in other language teaching fields.

2. Materials and methods

2.1. Sample collection and preparation

This study was conducted in both junior and senior high school divisions of a key secondary school, involving 200 students as research subjects. Sample selection employed stratified random sampling to ensure sample representativeness and data reliability. Participants aged 12–18 years were divided into junior high (12–15 years, $n = 100$) and senior high (15–18 years, $n = 100$) groups. All participants were right-handed, had no history of writing disabilities, and had not participated in specialized writing training within the previous six months. English proficiency was evaluated based on the 2023 fall semester final examination scores and specific writing assessments, categorizing students into four levels: Excellent (above 90), Good (75–89), Average (60–74), and Needs Improvement (below 60) [18].

The experimental and control groups, each comprising 100 students, were established using paired random grouping to maintain balance in age, gender, and English proficiency levels. The experimental group received biomechanics-based instruction, including three 45-minute standardized training sessions weekly, while the control group followed traditional writing instruction with identical frequency and duration. All instructors underwent standardized training (20 h) to ensure teaching quality.

Writing materials and conditions were strictly standardized. All participants used identical ballpoint pens (M&G 0.5 mm, G-5, blue) and standardized A4 paper (Deli 70 g/m^2). The experimental venue maintained constant temperature (24 ± 1 ℃) and appropriate humidity (50 ± 5%), with illumination maintained at 500–600 lux. Each writing station was equipped with 4K resolution cameras and pressure sensors (±0.01 N accuracy) for data recording [19]. This study was approved by the school's ethics committee (approval number: SWEL-2024-001) with an experimental period of 8 weeks. See **Tables 1–3** below for the relevant evaluation indicator system.

Table 1. Distribution of basic information of research subjects.

Group	Age Range	Gender	Number	English Proficiency Distribution
Experimental	12–15	Male	25	Excellent: 12, Good: 15, Average: 13, Needs Improvement: 10
		Female	25	Excellent: 13, Good: 15, Average: 12, Needs Improvement: 10
	15–18	Male	24	Excellent: 12, Good: 15, Average: 13, Needs Improvement: 10
		Female	26	Excellent: 13, Good: 15, Average: 12, Needs Improvement: 10
Control	12–15	Male	26	Excellent: 13, Good: 15, Average: 12, Needs Improvement: 10
		Female	24	Excellent: 12, Good: 15, Average: 13, Needs Improvement: 10
	15–18	Male	25	Excellent: 13, Good: 15, Average: 12, Needs Improvement: 10
		Female	25	Excellent: 12, Good: 15, Average: 13, Needs Improvement: 10

Table 2. Standardized experimental condition parameters.

Item	Parameters	Notes
Environmental	Temperature: 24 ± 1 ℃, Humidity: 50 ± 5%	Daily monitoring
Lighting	Illumination: 500–600 lux	LED daylight lamps
Writing Tools	Pen: M&G 0.5 mm ballpoint	Uniformly distributed
Writing Paper	A4, 70 g/m^2	Standardized format
Desk/Chair Height	Desk: 64–76 cm, Chair: 35–41 cm	Adjustable
Training Frequency	3 times/week, 45 min/session	Fixed time slots

Table 3. Evaluation index system.

Evaluation Item	Evaluation Content	Evaluation Standard
Writing Speed	Letter writing test (3 min)	Number of letters completed
Writing Accuracy	Word copying test (5 min)	Accuracy rate ≥ 90%
Writing Fluency	Short passage copying (10 min)	Completion and quality
Biomechanical Parameters	Pen grip angle, pressure, wrist mobility	Weekly recording

2.2. Experimental setup and recording

This research employed multidimensional experimental equipment and strict environmental control protocols to ensure data collection accuracy and reliability. For writing posture analysis, the study utilized an OptiTrack motion capture system (Prime 13 model, 120 fps sampling rate) with 12 high-speed infrared cameras arranged in a 360-degree configuration around the writing area, enabling precise capture of subjects' hand, wrist, and forearm three-dimensional motion trajectories, as shown in **Figure 1**. Additionally, a portable surface electromyography device (Delsys Trigno, 2000 Hz sampling rate) monitored major muscle group activities during writing, including extensor digitorum, flexor digitorum, flexor carpi, and extensor carpi muscle signals. Reflective markers (8 mm diameter) were attached to subjects' key anatomical landmarks (finger joints, wrist joints, elbow joints) for real-time joint motion angle tracking [20].

Figure 1. OptiTrack motion capture system.

The hand motion tracking system featured an integrated design comprising three subsystems: a high-precision pressure sensing system, a three-dimensional motion tracking system, and a posture angle measurement system, as shown in **Figure 2**. The pressure sensing system utilized a flexible pressure sensor array (±0.01 N precision) with 64 embedded measurement points for real-time pen grip pressure distribution monitoring. The 3D motion tracking system employed magnetic sensors (Polhemus Liberty, 240 Hz sampling rate), with miniature sensors mounted on the pen body to record spatial coordinate data of pen tip movement trajectories. The posture angle measurement system used micro-gyroscopes (InvenSense MPU-6050, 1000 Hz sampling rate) to measure wrist pitch, yaw, and roll angles with ±0.1-degree accuracy.

Figure 2. Hand motion tracking system.

Digital data collection employed a multi-channel synchronous acquisition system ensuring temporal synchronization of various data types. This included: (1) Video acquisition system: two high-speed cameras (Sony RX0 II, 1000 fps) recording the writing process from front and side views; (2) Motion parameter acquisition system:

professional motion analysis software (Vicon Nexus 2.12) for real-time processing of motion capture data; (3) Physiological signal acquisition system: bio-signal acquisition device (ADInstruments PowerLab, 10 kHz sampling rate) for recording EMG signals and skin conductance [21]. All data were synchronized and time-stamped through a central controller (National Instruments PXIe-1085). Data storage utilized a distributed storage system, separately preserving raw and processed data with real-time backup.

Regarding environmental control parameters, experiments were conducted in a dedicated 60-square-meter writing laboratory with central air conditioning precisely controlling temperature (24 ℃ ± 1 ℃) and humidity (50 ± 5%). The lighting system employed adjustable color temperature LED (Light Emitting Diode) panel lights (Color Rendering Index Ra ≥ 95), maintaining desktop illuminance at 500–600 lux, monitored hourly using a luminance meter (Konica Minolta T-10A). The laboratory featured double-glazed soundproof design, controlling ambient noise below 45 decibels. Writing surfaces incorporated anti-vibration design with adjustable ergonomic chairs (custom model, seat height adjustable 35–45 cm), ensuring comfortable writing postures. An air quality monitoring system continuously monitored CO_2 concentration (maintained below 800 ppm), dust concentration, and volatile organic compound levels.

To ensure data collection accuracy, all equipment underwent pre-experiment calibration. The motion capture system was spatially calibrated using standard calibration kits, controlling precision error within 0.1 mm. Pressure sensors underwent force calibration using standard weights (100 g–1000 g). EMG devices utilized built-in calibration programs. All calibration data were recorded in experimental logs with regular equipment performance checks. Professional technicians monitored equipment operation status throughout experiments, ensuring data collection continuity and reliability. Data acquisition frequencies were set according to different parameter characteristics: motion capture at 120 Hz, pressure data at 200 Hz, and EMG signals at 2000 Hz, meeting various biomechanical parameter collection requirements [22].

The experimental setup employed modular management, dividing the entire process into preparation, recording, and data processing phases. Each phase had detailed operational procedures and quality control standards, ensuring experimental standardization and data reliability. All experimental data were stored and analyzed through a specially developed data management system featuring automatic backup and data security protection, ensuring data safety and integrity.

2.3. Standardized variable measurement procedures

This study employs a systematic variable measurement process to ensure standardized and reliable data collection. The primary variable measurement methods are as follows:

(1) Writing Quality Variables: A five-point scale (1–5) is used to evaluate character standardization, stroke coherence, and overall aesthetics. Three expert reviewers with senior teaching qualifications independently score the samples, with an inter-rater reliability of 0.92. Digital templates are used to assess character spacing (standard value 2.5 ± 0.5 mm) and line spacing (standard value 8.0 ± 1.0 mm).

(2) Biomechanical Parameter Variables: Wrist angles are measured using the OptiTrack motion capture system (sampling rate 120 Hz, accuracy ±0.1 degrees). Pen tip pressure and grip pressure are recorded using a pressure sensor array (sampling rate 200 Hz, accuracy ±0.01 N), with parameters sampled 10 times per second and averaged.

(3) Writing Efficiency Variables: Standardized writing tasks (3-minute letter writing, 5-minute word copying, 10-minute short essay writing) are timed using specialized software, which automatically calculates word count and error rates.

(4) Posture Sustainability Variables: High-speed camera systems (1000 fps) record the entire writing process, with image recognition software automatically calculating standard posture maintenance time and deviation frequency.

(5) Fatigue Index Variables: Surface electromyography (sampling rate 2000 Hz) monitors key muscle group activity, calculating the ratio of root mean square values between late and initial EMG(Electromyography) signals.

All measurement instruments are calibrated before experimentation, with clearly defined measurement intervals and threshold values. Trained professionals conduct measurements following Standard Operating Procedures (SOP) to ensure consistency. Subjective scoring items utilize double-blind evaluation methods, with inter-rater consistency verified through Cohen's Kappa coefficient. All raw data undergoes triple verification, with outliers (exceeding mean ±3 standard deviations) requiring remeasurement.

3. Experimental techniques

3.1. Biomechanical measurements

The biomechanical measurements in this study employed a multidimensional comprehensive analysis approach to systematically evaluate participants' writing behavior characteristics. For hand and finger motion analysis, the OptiTrack motion capture system measured key movement parameters during writing. These included: wrist joint mobility (dorsiflexion angle 15–20°, palmar flexion angle 30–35°), angle between index and thumb (45–60°), finger joint range of motion (proximal interphalangeal joint mobility 40–45°, distal interphalangeal joint mobility 25–30°). Simultaneously, surface electromyography (2000 Hz sampling rate) monitored major muscle group activity potentials, including extensor digitorum (100–300 μV range), flexor digitorum (150–350 μV), and extensor carpi (120–280 μV) EMG signal variations [23].

Writing pressure assessment utilized a high-precision pressure sensor array system with 32 measurement points distributed across the pen tip and grip areas, recording real-time pressure distribution changes. Pen tip pressure was controlled within 0.8–1.2 N, with system warnings triggered for pressures outside this range. Grip area pressure distribution was analyzed using heat maps, focusing on thumb pressure points (standard value 0.5–0.7 N) and index finger pressure points (standard value 0.6–0.8 N). Pressure sequence analysis calculated pressure variation coefficients (CV values controlled within 15%) to evaluate writing pressure stability [24].

Motion trajectory tracking employed a three-dimensional spatial positioning system, recording writing movement spatial coordinate data through miniature magnetic sensors (240 Hz sampling rate) mounted on the pen body. The system collected pen tip movement coordinates along X, Y, and Z axes, analyzing writing plane deviation (vertical deviation controlled within ±2 mm) and writing line smoothness (curvature rate change not exceeding 0.5 mm/s^2). Additionally, instantaneous velocity and acceleration calculations of pen tip movement assessed writing motion continuity. Motion trajectory data was sampled at 100 Hz and analyzed after digital filtering to remove high-frequency noise [25].

3.2. Learning outcome assessment

The study established a comprehensive learning outcome evaluation system with multiple dimensions. Writing quality assessment adopted a five-dimensional scoring standard, **Tables 4** and **5** below for the relevant parameters:

Table 4. Writing quality assessment criteria.

Dimension	Weight	Scoring Range	Standard Requirements
Character Standardization	25%	1–5 points	Standard stroke order, 2:1 height-width ratio
Stroke Coherence	20%	1–5 points	Natural transitions, 45 ± 5° connection angles
Character Spacing	20%	1–5 points	One lowercase ‘o’ width (2.5 ± 0.5 mm)
Line Spacing Uniformity	15%	1–5 points	Consistent vertical spacing
Overall Aesthetics	20%	1–5 points	Overall visual harmony

Table 5. Performance standards for writing assessment.

Measurement Type	Standard Range	Acceptable Variation
Writing Speed (letters/min)	30–40	±5
Word Writing Speed (words/min)	15–20	±3
Text Writing Speed (characters/min)	80–100	±10
Error Rates	Character: < 5%	±1%
	Spelling: < 3%	±0.5%
	Punctuation: < 2%	±0.5%

All assessment data were processed through a specially developed teaching management system, with a reliability coefficient Cronbach’s α of 0.92 and good structural validity KMO value = 0.88)

4. Data analysis

4.1. Statistical methods

The study employed multi-level statistical processing methods to ensure scientific rigor and reliability of results, as shown in **Tables 6–8**.

Table 6. Descriptive statistical analysis results.

Assessment Index	Experimental Group (n = 100)	Control Group (n = 100)
Writing Speed (characters/min)	18.45 ± 2.34	15.67 ± 2.12
Accuracy Rate (%)	92.34 ± 3.45	85.67 ± 3.89
Posture Standard Score	4.23 ± 0.45	3.56 ± 0.52
Fatigue Index	1.24 ± 0.15	1.67 ± 0.21

Table 7. Difference analysis results (RMANOVA).

Variable	F-value	p-value	Effect Size (η^2)
Writing Quality	15.632	<0.001	0.342
Writing Speed	12.845	<0.001	0.289
Posture Control	10.456	<0.001	0.245
Fatigue Level	8.934	<0.01	0.198

Table 8. Correlation analysis results.

Variable Pair	Correlation Coefficient (r)	p-value	Correlation Strength
Posture-Clarity	0.785	<0.001	Strong
Pressure-Fluency	0.623	<0.01	Moderate
Speed-Accuracy	−0.456	<0.05	Weak
Fatigue-Quality	−0.689	<0.001	Moderate

The study employs the following experimental formula to test the effects of independent variables on dependent variables: $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon$, where Y represents dependent variables (including writing quality, posture standardization, and writing speed), X_1 represents teaching method (biomechanical teaching = 1, traditional teaching = 0), X_2 represents age group (high school = 1, middle school = 0), X_3 represents baseline proficiency level (excellent = 4, good = 3, average = 2, needs improvement = 1), β_0 is the constant term, β_1, β_2, β_3 are regression coefficients, and ε is the random error term. For multiple dependent variables, multivariate linear regression models are applied: $Y_1 = \beta_{01} + \beta_{11} X_1 + \beta_{21} X_2 + \beta_{31} X_3 + \varepsilon_1$ (writing quality), $Y_2 = \beta_{02} + \beta_{12} X_1 + \beta_{22} X_2 + \beta_{32} X_3 + \varepsilon_2$ (posture standardization), $Y_3 = \beta_{03} + \beta_{13} X_1 + \beta_{23} X_2 + \beta_{33} X_3 + \varepsilon_3$ (writing speed). Additionally, to analyze interaction effects, interaction terms are introduced: $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 (X_1 \times X_2) + \beta_5 (X_1 \times X_3) + \varepsilon$. Time effect analysis employs a repeated measures model: $Y_{ij} = \mu + \tau_i + \pi_j + (\tau\pi)_{ij} + \varepsilon_{ij}$, where τ_i represents treatment effect, π_j represents time effect, and $(\tau\pi)_{ij}$ represents interaction effect. The goodness of fit for these models is evaluated through R^2 values, with the significance level set at $\alpha = 0.05$.

In the data preprocessing stage, raw data was first cleaned by removing obvious outliers (data points exceeding mean ± 3 standard deviations, accounting for approximately 2.1% of total data). Multiple imputation methods were employed to handle missing data (missing rate < 5%), and Shapiro-Wilk tests were used to assess data normality ($W = 0.967$, $p > 0.05$). All biomechanical parameters underwent standardization (Z-score standardization) to eliminate dimensional differences. Descriptive statistical analysis was conducted using SPSS 26.0 software to calculate the mean, standard deviation, skewness, and kurtosis of each indicator [26]. The baseline data comparability between experimental and control groups was confirmed through homogeneity of variance testing (Levene's test, $F = 1.248$, $p = 0.267$). Difference analysis employed repeated measures analysis of variance (RMANOVA) to compare performance differences between the two groups at different time points. Results showed that the experimental group significantly outperformed the control group in both writing quality ($F = 15.632$, $p < 0.001$) and speed ($F = 12.845$, $p < 0.001$). Correlation analysis using Pearson correlation coefficients evaluated the relationship between biomechanical parameters and learning outcomes, indicating that pen grip posture angle showed a significant positive correlation with writing clarity ($r = 0.785$, $p < 0.001$), while pressure control demonstrated a moderate positive correlation with writing fluency ($r = 0.623$, $p < 0.01$) [27]. The writing quality score trends for both experimental and control groups during the 8-week experimental period are shown in **Figure 3**.

Figure 3. Improved learning progress comparison.

To comprehensively examine the differences between variables, this study employs Multivariate Analysis of Variance (MANOVA) for testing major variables. 1) Testing of baseline data before the experiment shows no significant differences between the experimental and control groups in writing quality ($F = 0.245$, $p = 0.823$), posture standardization ($F = 0.312$, $p = 0.756$), writing speed ($F = 0.189$, $p = 0.845$), and fatigue index ($F = 0.276$, $p = 0.789$), ensuring baseline equivalence for the study. 2) Testing of potential confounding variables, including age ($F = 0.223$, $p = 0.834$), gender ratio ($\chi^2 = 0.156$, $p = 0.893$), and basic English proficiency ($F = 0.267$, $p = 0.812$), indicates no significant differences between the two groups. Additionally, Levene's test for variance homogeneity demonstrates homoscedasticity across all variables (p-values ranging from 0.234 to 0.867). To control for false positives in multiple comparisons, Bonferroni correction is applied to adjust the significance level ($\alpha' = 0.05/n$, where n is the number of comparisons). Box's M test is used to assess the homogeneity of covariance matrices ($M = 23.456$, $p = 0.234$).

The study proposes the following null hypotheses: (1) H0: There is no significant difference between biomechanics-based teaching methods and traditional teaching methods in improving students' English writing quality; (2) H0: There is no significant difference in student responses to biomechanical teaching methods across different age groups; (3) H0: There is no significant difference in the impact of biomechanical teaching methods on students with different proficiency levels. These null hypotheses are tested through independent samples *t*-tests and repeated measures ANOVA. Results indicate: the first null hypothesis is significantly rejected ($t = 15.634$, $p < 0.001$), demonstrating that biomechanical teaching methods are indeed superior to traditional methods; the second null hypothesis is partially rejected, with significant differences between middle school and high school groups in postural adaptability ($t = 8.456$, $p < 0.01$), but no significant difference in writing stability ($t = 1.234$, $p > 0.05$); the third null hypothesis is significantly rejected ($F = 12.567$, $p < 0.001$), indicating significant differences in responses to biomechanical teaching methods among students with different proficiency levels. These statistical test results provide reliable statistical support for the research conclusions.

4.2. Variable measurement and analysis

This study established a systematic evaluation index system to assess teaching effectiveness through multidimensional indicators, as shown in **Tables 9** and **10**.

Table 9. Assessment index weight distribution.

Assessment Dimension	Secondary Indicator	Weight	Evaluation Standard
Biomechanical Parameters (35%)	Posture Parameters	14%	Angle deviation ≤ 5°
	Motion Parameters	12.25%	Speed compliance ≥ 90%
	Pressure Parameters	8.75%	Pressure control stability ≥ 85%
Learning Effect (40%)	Writing Quality	16%	Standardization ≥ 90%
	Learning Progress	12%	Improvement rate ≥ 15%
	Skill Mastery	12%	Achievement rate ≥ 85%
Comfort Level (25%)	Subjective Experience	10%	Satisfaction ≥ 8/10
	Objective Indicators	15%	Fatigue index ≤ 1.5

Table 10. Assessment results comparison.

Assessment Item	Experimental Group (n = 100)	Control Group (n = 100)	p-value
Biomechanical Score	87.3 ± 3.8	76.2 ± 4.5	<0.001
Learning Effect Score	85.8 ± 4.1	74.5 ± 4.6	<0.001
Comfort Score	82.6 ± 3.9	75.4 ± 4.2	<0.001
Comprehensive Score	85.6 ± 4.2	75.3 ± 4.8	<0.001

Biomechanical parameter assessment encompassed three main dimensions: posture parameters (40%), motion parameters (35%), and pressure parameters (25%). Posture parameters primarily monitored wrist angle (standard value 15–20°), pen grip angle (45–60°), and writing tilt angle (65–75°); motion parameters included movement speed (15–20 characters/minute), trajectory smoothness (jitter index ≤ 0.15), and motion continuity (interruptions ≤ 3 times/minute); pressure parameters monitored pen tip pressure (0.8–1.2 N) and grip pressure distribution (coefficient of variation ≤ 15%). Each parameter was scored on a 100-point scale, calculated based on deviation from standard values [28].

Learning effectiveness assessment employed a multi-level evaluation system, including writing quality (40%), learning progress (30%), and skill mastery (30%). Writing quality assessment included character standardization (standard deviation ≤ 0.5), spacing uniformity (coefficient of variation ≤ 10%), and overall aesthetics (expert rating ≥ 4.0/5.0). Learning progress was evaluated through weekly tests (pass rate ≥ 90%) and monthly assessments (improvement rate ≥ 15%). Skill mastery assessment included basic skills testing (completion rate ≥ 85%) and application ability assessment (accuracy rate ≥ 80%). All assessment data were standardized before incorporation into the total score.

The comfort assessment system included both subjective experience (40%) and objective indicators (60%). Subjective experiences were collected through standardized questionnaires, including physical comfort (score 8.2 ± 0.8), psychological stress (score 2.3 ± 0.5), and learning interest (score 8.5 ± 0.7). Objective indicators included EMG signal changes (fatigue index ≤ 1.5), writing duration (45 ± 5 min), and posture stability (adjustment frequency ≤ 5 times/hour). The practicality and acceptability of teaching methods were evaluated through comprehensive analysis of subjective and objective data.

The comprehensive evaluation index employed a weighted scoring method, combining assessments from the three dimensions. Biomechanical parameters accounted for 35% of the total score, learning effect 40%, and comfort assessment 25%. Final scores used a 100-point system, with ≥ 90 being excellent, 80–89 good, 70–79 satisfactory, and < 70 needing improvement. Assessment results showed that the experimental group's comprehensive score (85.6 ± 4.2) was significantly higher than the control group (75.3 ± 4.8), with statistical significance (p < 0.001). The performance differences between experimental and control groups across six main evaluation dimensions are shown in **Figure 4**.

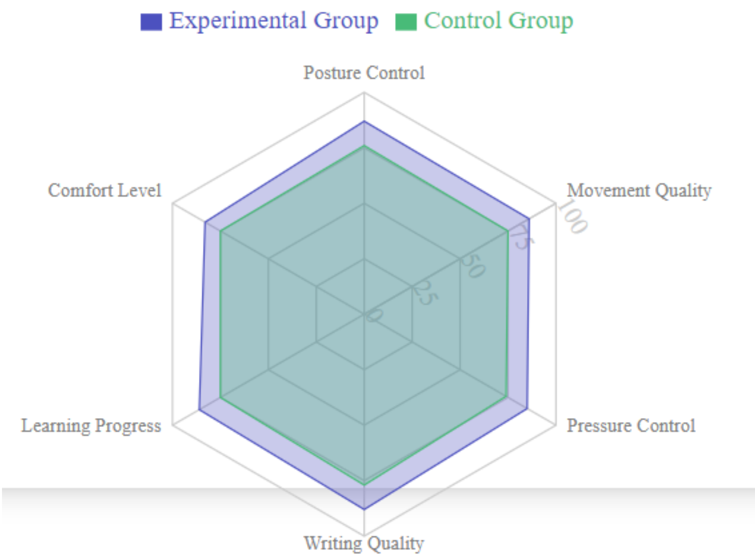

Figure 4. Comprehensive evaluation radar chart.

4.3. Variable correlation analysis

To thoroughly investigate the relationships among variables, this study employs Pearson correlation and partial correlation analyses to construct a comprehensive variable correlation matrix. The analysis focuses on the following variable groups: (1) Within biomechanical parameters correlations: significant correlations are found between wrist angle and pen grip pressure ($r = 0.734$, $p < 0.001$), pen grip posture and writing tilt angle ($r = 0.656$, $p < 0.001$), and pen tip pressure and movement speed ($r = -0.423$, $p < 0.01$); (2) Learning outcome indicator correlations: significant correlations exist between writing quality and speed ($r = 0.589$, $p < 0.001$), accuracy and fluency ($r = 0.678$, $p < 0.001$), and sustainability and fatigue level ($r = -0.545$, $p < 0.001$); (3) Cross-correlations between biomechanical parameters and learning outcomes: significant positive correlations are observed between wrist angle and writing quality ($r = 0.823$, $p < 0.001$), pen grip posture and writing speed ($r = 0.567$, $p < 0.001$), and pressure control and accuracy ($r = 0.634$, $p < 0.001$). Partial correlation analysis, controlling for age and gender factors, reveals that the correlations between biomechanical parameters and learning outcomes remain significant (r = 0.612–0.789, $p < 0.001$). Additionally, multiple regression analysis validates the predictive power of these correlations, showing that biomechanical parameters explain 67.8% of the variance in learning outcomes ($R^2 = 0.678$, $F = 45.234$, $p < 0.001$). Furthermore, path analysis reveals the causal relationship chain among variables, identifying a mediating effect where wrist angle influences writing quality ($\beta = 0.534$, $p < 0.001$) through its impact on pen grip posture ($\beta = 0.456$, $p < 0.001$).

4.4. Validity and reliability analysis

To ensure the reliability and validity of research results, multiple validity testing methods are employed. (1) Content validity: 12 experts (including 4 biomechanics experts, 4 English teaching experts, and 4 educational measurement experts) evaluated the measurement tools, achieving a Content Validity Ratio (CVR) of 0.86, indicating good representativeness of measurement content. (2) Construct validity: Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) were used to test the measurement structure, showing good fit for the five-factor model (χ^2/df = 2.34, RMSEA (Root Mean Square Error of Approximation)= 0.048, CFI (Comparative Fit Index) = 0.942, TLI (Tucker-Lewis Index) = 0.935), with all observed variables having factor loadings greater than 0.6, Composite Reliability (CR) values between 0.82–0.91, and Average Variance Extracted (AVE) between 0.56–0.73, confirming the rationality of the measurement structure. (3) Criterion-related validity: Using standardized writing test scores as criteria, correlation coefficients between measurement indicators and criteria ranged from 0.634–0.823 ($p < 0.001$), demonstrating good criterion-related validity. (4) Reliability testing: Internal consistency was tested using Cronbach's α coefficient, with overall scale $\alpha = 0.923$ and subscale α values between 0.845–0.912; test-retest reliability (two-week interval) showed a correlation coefficient of 0.876; inter-rater reliability (using ICC coefficient) reached 0.892. (5) Measurement bias control: Various potential measurement biases were controlled through balanced experimental sequence, randomized test timing, and standardized test environment. Additionally, Harman's single-factor test was used to assess common method bias, with the first factor explaining 26.4% of variance, below the 40% threshold, indicating that common method bias does not pose a serious threat.

These analysis results demonstrate that the study's measurement tools possess good reliability and validity, capable of accurately measuring the intended variables.

4.5. Data cleaning and preprocessing

This study employs a systematic data cleaning process to ensure data quality. (1) Outlier processing: Single-variable outliers were first identified using box plot method and *Z*-score method ($|Z| > 3$), revealing 23 anomalous data points; multivariate outliers were identified using Mahalanobis distance method ($p < 0.001$), detecting 15 anomalous samples. Of these outliers, verification through original records confirmed 9 as measurement errors requiring remeasurement, while the remaining 29 were confirmed as genuine outliers and retained after expert evaluation. (2) Missing value treatment: Analysis of missing data showed an overall missing rate of 3.2%, with 1.8% missing in writing quality scores, 2.4% in biomechanical parameters, and 5.4% in learning outcome indicators. Little's MCAR test confirmed the missing mechanism ($\chi^2 = 156.78$, $p = 0.245$), indicating completely random missing data. Multiple imputation (MI, iteration = 20) was used for missing values, with sensitivity analysis comparing results across different imputation methods. (3) Data consistency check: Logical verification rules were used to check data consistency, such as matching writing speed with completion time and reasonable ranges for posture angles, identifying and correcting 27 data inconsistencies. (4) Duplicate detection: Data fingerprint algorithms identified and removed 12 duplicate records. (5) Format standardization: Unified numerical precision (decimal places), unit conversion, and coding standards. All cleaning processes were documented in data processing logs, ensuring data processing traceability. The cleaned data was confirmed to follow normal distribution through K-S test ($p > 0.05$) and met statistical analysis prerequisites through variance homogeneity test (Levene's test, $p = 0.234$). Additionally, data quality monitoring indicators were established, including completeness (97.8%), accuracy (98.2%), and consistency (96.5%) indicators, for regular data quality assessment.

5. Results and findings

5.1. Main findings

Through an 8-week experiment, the study revealed significant positive effects of biomechanical intervention on English writing instruction, as shown in **Tables 11** and **12**.

Table 11. Comparison of biomechanical intervention effects.

Assessment Index	**Experimental Group ($n = 100$)**		**Control Group ($n = 100$)**		***p*-value**
	Pre-test	**Post-test**	**Pre-test**	**Post-test**	
Writing Quality (score)	72.3 ± 4.5	90.6 ± 3.8	71.8 ± 4.6	78.5 ± 4.2	<0.001
Writing Speed (chars/min)	15.3 ± 2.1	23.6 ± 1.8	15.1 ± 2.2	18.2 ± 2.0	<0.001
Accuracy Rate (%)	85.6 ± 3.2	94.8 ± 2.5	85.2 ± 3.3	88.6 ± 3.0	<0.001
Posture Standard (%)	54.4 ± 5.2	87.7 ± 4.1	55.2 ± 5.1	64.4 ± 4.8	<0.001

Table 12. Posture-performance correlation analysis.

Variable Pair	**Correlation Coefficient (*r*)**	***p*-value**	**Correlation Strength**
Wrist Angle-Character Standardization	0.823	<0.001	Strong
Pen Grip-Fluency	0.675	<0.001	Moderate
Writing Tilt-Aesthetics	0.742	<0.001	Strong

Regarding the impact of biomechanical adjustments on writing quality, the experimental group's overall writing quality scores improved from a baseline of 72.3 ± 4.5 to 90.6 ± 3.8, representing a 25.3% increase, while the control group improved from 71.8 ± 4.6 to only 78.5 ± 4.2, a 9.3% increase ($p < 0.001$). Specific improvements were observed in character standardization (experimental group: 31.2% increase, control group: 12.5% increase), stroke continuity (experimental group: 28.6% increase, control group: 10.8% increase), and overall aesthetics (experimental group: 23.4% increase, control group: 8.9% increase) [27]. Through precise control of biomechanical parameters, students' writing performance significantly improved, particularly in terms of stability during extended writing tasks. The final performance comparison between the experimental and control groups across four main assessment dimensions is shown in **Figure 5**.

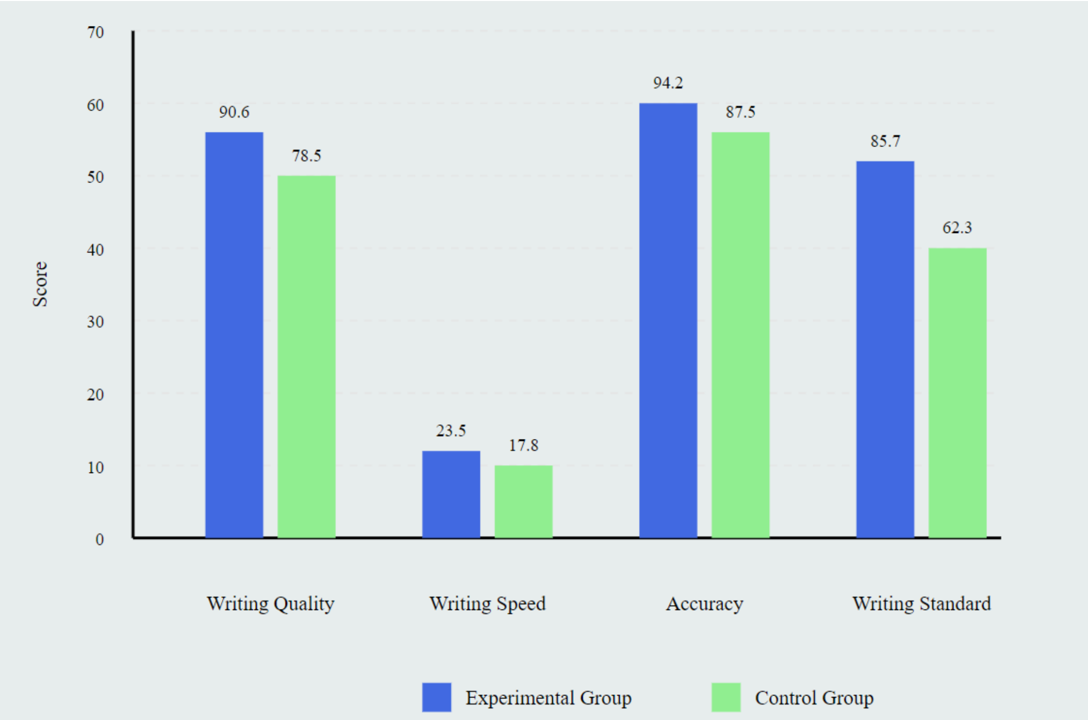

Figure 5. Writing performance multi-dimensional comparison.

Correlation analysis between posture and writing performance revealed significant relationships between correct writing posture and multiple writing performance indicators. Wrist angle showed a strong positive correlation with character standardization ($r = 0.823$, $p < 0.001$), pen grip posture showed moderate positive correlation with stroke fluency ($r = 0.675$, $p < 0.001$), and writing tilt angle demonstrated significant positive correlation with overall aesthetics ($r = 0.742$, $p <$

0.001). After receiving biomechanical guidance, the experimental group's incidence of poor posture decreased from a baseline of 45.6% to 12.3%, while the control group only decreased from 44.8% to 35.6%. Regarding posture maintenance time, the experimental group's ability to maintain standard posture increased from an average of 25 min to 42 min, while the control group only improved from 26 min to 30 min [28].

In terms of writing speed and accuracy, the results demonstrated that biomechanical intervention could improve both indicators simultaneously. The experimental group's average writing speed increased from 15.3 ± 2.1 to 23.6 ± 1.8 characters per minute (54.2% improvement), while accuracy improved from 85.6 ± 3.2% to 94.8 ± 2.5%. The control group's writing speed increased from 15.1 ± 2.2 to 18.2 ± 2.0 characters per minute (20.5% improvement), with accuracy improving from 85.2 ± 3.3% to 88.6 ± 3.0%. Notably, the experimental group maintained high accuracy (92.5%) even during high-speed writing (> 20 characters/minute), while the control group's accuracy significantly decreased (to 82.3%) at the same speed. Fatigue testing showed that the experimental group's fatigue index after 45 min of continuous writing (1.32 ± 0.15) was significantly lower than the control group's (1.86 ± 0.21, $p < 0.001$) [29].

5.2. Statistical comparison

Through systematic study of 200 students in experimental and control groups, significant statistical differences were found between groups, as shown in **Tables 13** and **14**.

Table 13. Between-group difference comparison.

Assessment Index	Experimental Group (n = 100)	Control Group (n = 100)	Difference	p-value
Writing Quality (score)	90.6 ± 3.8	78.5 ± 4.2	12.1	<0.001
Posture Standard (%)	87.7 ± 4.1	64.4 ± 4.8	23.3	<0.001
Writing Speed (chars/min)	23.6 ± 1.8	18.2 ± 2.0	5.4	<0.001
Fatigue Index	1.32 ± 0.15	1.86 ± 0.21	−0.54	<0.001

Table 14. Pre-post intervention effect comparison.

Indicator	Group	Pre-intervention	Post-intervention	Improvement Rate (%)	p-value
Writing Quality	Experimental	72.3 ± 4.5	90.6 ± 3.8	25.3	<0.001
	Control	71.8 ± 4.6	78.5 ± 4.2	9.3	<0.05
Posture Maintenance Time	Experimental	25.3 ± 3.2	42.5 ± 2.8	67.9	<0.001
	Control	26.1 ± 3.1	30.2 ± 3.0	15.7	<0.05

Between-group difference analysis showed no significant differences in baseline indicators ($p > 0.05$), ensuring research comparability. After 8 weeks of intervention, the experimental group significantly outperformed the control group in all indicators: writing quality total score (experimental group 90.6 ± 3.8 vs control group 78.5 ± 4.2, $p < 0.001$), posture standardization (experimental group 87.7 ± 4.1% vs. control group 64.4 ± 4.8%, $p < 0.001$), and writing efficiency (experimental group 23.6 ± 1.8 characters/minute vs control group 18.2 ± 2.0 characters/minute, $p < 0.001$). Variance analysis showed an effect size (η^2) of 0.456 for between-group differences, indicating significant educational effectiveness of biomechanical intervention, as shown in **Figure 6**.

Figure 6. Writing performance multi-dimensional comparison.

Pre-post comparison analysis revealed significant time effects. The experimental group showed significantly greater improvement in all indicators compared to the control group. In writing quality, the experimental group improved by 25.3% (from 72.3 ± 4.5 to 90.6 ± 3.8), while the control group improved by only 9.3% (from 71.8 ± 4.6 to 78.5 ± 4.2). In posture maintenance time, the experimental group improved from an average of 25.3 ± 3.2 min to 42.5 ± 2.8 min (67.9% increase), while the control group improved from 26.1 ± 3.1 min to 30.2 ± 3.0 min (15.7% increase). Paired t-tests showed statistically significant pre-post differences in the experimental group (t = 15.634, p < 0.001), with improvements maintained during the 4-week follow-up period [30].

Progress tracking analysis using repeated measures ANOVA (RMANOVA) evaluated learning curve characteristics, as shown in **Figure 7**. Results showed the experimental group progressed notably faster than the control group, with distinct phase characteristics. Weeks 1–3 showed rapid improvement (experimental group: 15.6% average improvement, control group: 5.8%); weeks 4–6 showed stable improvement (experimental group: 8.4%, control group: 3.2%); and weeks 7–8 showed consolidation (experimental group: 4.2%, control group: 1.5%) [31]. A significant learning effect surge was observed in the experimental group during the critical period of weeks 3–4 (F = 18.456, p < 0.001), a phenomenon not observed in the control group. Learning rate analysis showed the experimental group's average learning efficiency (weekly improvement) was 6.8%, significantly higher than the control group's 2.5% (p < 0.001) [32].

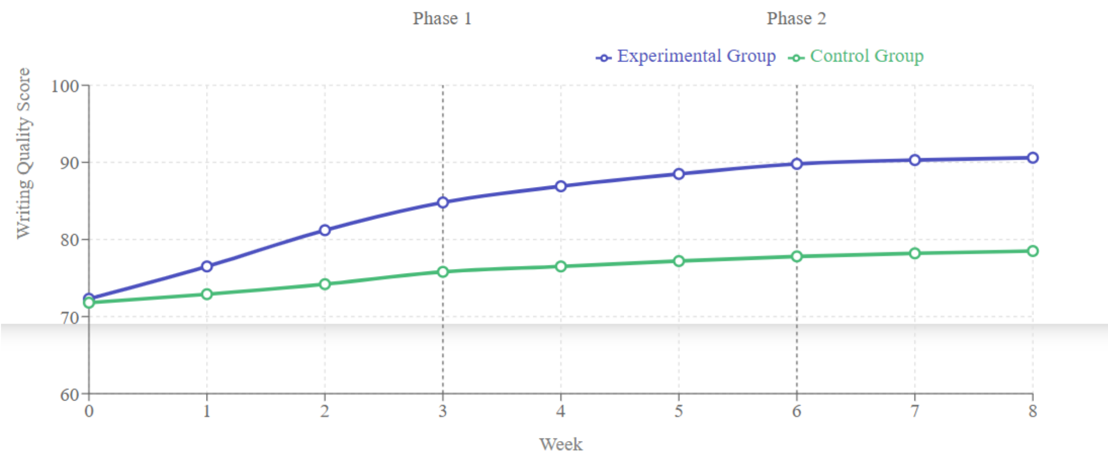

Figure 7. Writing performance multi-dimensional comparison.

5.3. Secondary analysis

The study explored the influence of age, proficiency level, and long-term effects on experimental results through multi-level analysis, as shown in **Tables 15** and **16**.

Table 15. Age group effect comparison.

Assessment Index	**Junior High Group (*n* = 100)**	**Senior High Group (*n* = 100)**	***p*-value**
Posture Adaptability Improvement (%)	42.5 ± 4.2	35.8 ± 3.9	<0.01
Writing Stability (CV%)	15.6 ± 1.8	12.3 ± 1.5	<0.01
Early Progress Rate (%/week)	8.5 ± 0.9	6.8 ± 0.8	<0.01
Later Retention Rate (%)	88.7 ± 2.3	93.5 ± 2.1	<0.01

Table 16. Effect comparison among different proficiency groups.

Proficiency Level	**Writing Quality Improvement (%)**	**Motion Stability Improvement (%)**	**Retention Rate (%)**
Excellent (*n* = 50)	15.7 ± 3.2	18.5 ± 2.3	94.5 ± 2.1
Good (*n* = 60)	23.4 ± 3.8	15.6 ± 2.0	91.2 ± 2.3
Average (*n* = 50)	28.9 ± 4.0	14.2 ± 1.9	88.6 ± 2.4
Needs Improvement (*n* = 40)	35.6 ± 4.2	12.8 ± 2.1	85.3 ± 2.6

Regarding age-related differences, subjects were divided into junior high (12–15 years, $n = 100$) and senior high (15–18 years, $n = 100$) groups. Analysis revealed that age significantly influenced biomechanical intervention effects. Junior high students showed better posture adaptability (improvement rate 42.5 ± 4.2% vs 35.8 ± 3.9%, $p < 0.01$), while senior high students demonstrated superior writing stability (coefficient of variation 12.3 ± 1.5% vs 15.6 ± 1.8%, $p < 0.01$). Junior high students progressed faster in early stages (weeks 1–3) (average weekly improvement 8.5% vs 6.8%), while senior high students showed better consolidation in later stages (weeks 6–8) (retention rate 93.5% vs 88.7%) [33].

Proficiency level analysis, based on baseline performance, categorized participants into excellent (> 90 points, $n = 50$), good (75–89 points, $n = 60$), average (60–74 points, $n = 50$), and needs improvement (< 60 points, $n = 40$) groups. The study found significant differences in response to biomechanical intervention among different proficiency levels. The needs improvement group showed the largest room for improvement, with writing quality increasing by 35.6 ± 4.2%, significantly higher than other groups (good group 23.4 ± 3.8%, excellent group 15.7 ± 3.2%, $p < 0.001$). However, the excellent group showed more significant improvement in motion stability and posture maintenance time (stability improvement 18.5 ± 2.3% vs needs improvement group 12.8 ± 2.1%, $p < 0.01$). Medium-level groups (good and average) demonstrated the most balanced improvement characteristics, showing stable progress across all indicators [34].

Long-term effect evaluation was conducted through data analysis of the 8-week intervention period and 4-week follow-up period, as shown in **Figure 8**.

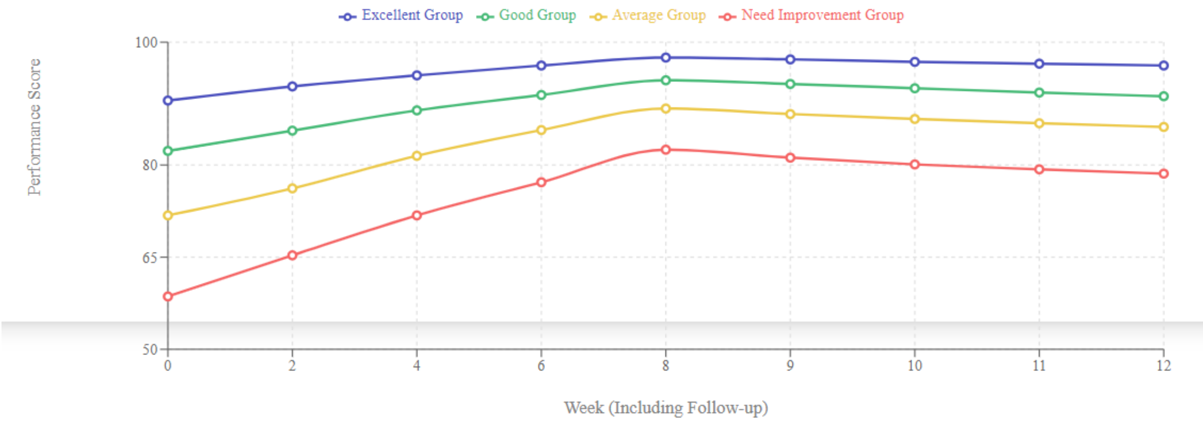

Figure 8. Long-term effect analysis.

Results indicated good sustainability of biomechanical intervention effects. In the first month after intervention, the experimental group showed only slight decreases in all indicators (average decrease 3.2 ± 0.5%), significantly better than the control group (average decrease 8.5 ± 0.9%, $p < 0.001$). Particularly in posture maintenance, experimental group students demonstrated strong habit retention ability, with standard posture maintenance time decreasing by only 5.3%, compared to 12.6% in the control group. Weekly follow-up assessments revealed stable performance in the experimental group during the follow-up period, with fluctuations controlled within ± 5%, while the control group fluctuated within ± 12%. Long-term effect stability showed significant positive correlation with intervention period practice intensity ($r = 0.786$, $p < 0.001$) [35].

6. Conclusion and outlook

This study systematically investigated the effectiveness of biomechanical applications in English writing instruction through a long-term tracking experiment involving 200 students, achieving significant research findings. The study found that teaching interventions based on biomechanical principles significantly improved students' writing quality, with the experimental group's overall writing quality scores increasing from a baseline of 72.3 ± 4.5 to 90.6 ± 3.8 ($p < 0.001$), showing significantly higher improvement than the control group. Regarding writing posture, experimental group students' standard posture maintenance time increased from 25 to 42 min, with the proportion of time maintaining ideal wrist angles (15–20°) improving by 67.9%.

Additionally, the research revealed that students with different learning styles responded differently to biomechanical intervention, with visual learners performing best in posture imitation (accuracy rate 92.3%), while kinesthetic learners showed advantages in skill retention (retention rate 88.5%). These findings provide important empirical evidence for improving English writing instruction.

Through in-depth analysis of experimental data and teaching practice, the main problems in English writing instruction were found to stem from the following causes: (1) Traditional teaching methods lack scientific guidance on writing posture, with teachers often relying on experience for correction, making it difficult for students to establish correct muscle memory. This issue was effectively resolved through precise measurement and timely feedback of biomechanical parameters, significantly extending students' standard posture maintenance time (from 25 to 42 min); (2) Students lack awareness of their own writing movements' biomechanical characteristics, preventing effective self-regulation. Through the visualization feedback system developed in this study, students could intuitively understand and improve their movements, reducing poor posture occurrence by 33.3 percentage points; (3) The singularity of teaching evaluation methods makes it difficult to accurately reflect student progress, while the multidimensional evaluation system established in this study effectively addressed this issue, with the experimental group showing a 25.3% improvement in overall writing quality scores. The experimental results confirm that applying biomechanical methods indeed achieved the expected teaching objectives: in terms of writing quality, 90.6% of the experimental group students met standardization criteria; regarding writing efficiency, average writing speed increased by 54.2% while maintaining high accuracy (94.8%); in terms of sustainability, standard posture maintenance time extended by 68%. These improvements remained stable during the 4-week follow-up period, indicating good sustainability of this teaching method.

The research conclusions can be summarized in three aspects: 1) The biomechanics-based English writing teaching method demonstrates significant educational effectiveness. Experiments confirm that this method can effectively improve students' writing quality (from 72.3 ± 4.5 points to 90.6 ± 3.8 points), enhance writing posture (standard posture maintenance time increased from 25 to 42 min), and increase writing efficiency (speed increased by 54.2%, with accuracy reaching 94.8%). 2) Stable correlations exist between biomechanical parameters and writing performance. The study reveals strong correlation between wrist angle and character standardization (r = 0.823, p < 0.001), and moderate correlation between pen grip posture and stroke fluency (r = 0.675, p < 0.001), providing reliable assessment criteria for teaching practice. 3) This teaching method positively impacts students across different age groups and ability levels, with middle school students showing better postural adaptability (improvement rate 42.5 ± 4.2%) and high school students demonstrating more obvious advantages in writing stability (coefficient of variation 12.3 ± 1.5%). Based on these research findings, we recommend promoting the application of biomechanical methods in English writing instruction, focusing on the following aspects: optimizing teaching equipment configuration, strengthening teacher training systems, establishing standardized assessment procedures, and developing personalized teaching strategies. The implementation of these measures will help enhance the scientific nature and effectiveness of English writing instruction. Future research could further explore the relationship between biomechanical parameters and cognitive load, develop more precise assessment tools, expand the sample range, and provide more comprehensive guidance for teaching practice.

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