Biomechanical analysis of the push-up exercise in university male student-athletes from different specializations: a sport-based comparative study

Análisis biomecánico del ejercicio de flexión de brazos en estudiantes-atletas universitarios varones de diferentes especializaciones: un estudio comparativo basado en el deporte

Authors

Runping Wu [1]
Chairat Choosakul [1]

[1] Mahasarakham University (Thailand)

Corresponding author:
Chairat Choosakul
chairat.c@msu.ac.th

Received: 09-11-25
Accepted: 20-12-25

How to cite in APA

Wu, R., & Choosakul, C. (2026). Biomechanical analysis of the push-up exercise in university male student-athletes from different specializations: a sport-based comparative study. *Retos, 75*, 557-571. https://doi.org/10.47197/retos.v75.118076

Abstract

Introduction: Sport-specific training may shape the neuromuscular strategies used in fundamental movements such as the push-up.
Objective: To compare the kinematic, kinetic, and electromyographic characteristics of push-ups among athletes from gymnastics, swimming, track and field, and basketball.
Methodology: Eighty male university athletes performed standardized push-ups while three-dimensional motion capture, dual force platforms, and surface electromyography recorded movement, force, and muscle activation patterns. Group differences were examined using multivariate and univariate analyses of variance, with effect sizes reported to quantify practical relevance ($\alpha = 0.05$).
Results: Gymnasts showed superior trunk stability and high co-activation; swimmers exhibited greater shoulder mobility but reduced core stability; and sprinters and basketball players demonstrated higher force development rates and faster concentric tempos.
Discussion: Distinct biomechanical "signatures" reflected sport-specific neuromuscular adaptations.
Conclusion: Push-up execution reveals underlying specialization-driven motor control strategies, offering valuable applications for individualized training, performance analysis, and injury prevention.

Keywords

Push-up biomechanics, sport specialization, neuromuscular adaptation, electromyography (EMG), kinematic and kinetic analysis.

Resumen

Introducción: El entrenamiento específico para cada deporte puede moldear las estrategias neuromusculares utilizadas en movimientos fundamentales como las flexiones.
Objetivo: Comparar las características cinemáticas, cinéticas y electromiográficas de las flexiones en atletas de gimnasia, natación, atletismo y baloncesto.
Metodología: Ochenta atletas universitarios masculinos realizaron flexiones estandarizadas mientras la captura de movimiento tridimensional, plataformas de fuerza dual y electromiografía de superficie registraban el movimiento, la fuerza y los patrones de activación muscular. Las diferencias entre los grupos se examinaron mediante análisis de varianza multivariados y univariados, con tamaños del efecto reportados para cuantificar la relevancia práctica ($\alpha = 0{,}05$).
Resultados: Los gimnastas mostraron una mayor estabilidad del tronco y una alta coactivación; los nadadores exhibieron una mayor movilidad del hombro, pero una menor estabilidad del core; y los velocistas y jugadores de baloncesto demostraron mayores tasas de desarrollo de fuerza y ritmos concéntricos más rápidos.
Discusión: Las distintas características biomecánicas reflejaron adaptaciones neuromusculares específicas del deporte. Conclusión: La ejecución de flexiones revela estrategias subyacentes de control motor impulsadas por la especialización, lo que ofrece aplicaciones valiosas para el entrenamiento individualizado, el análisis del rendimiento y la prevención de lesiones.

Palabras clave

Biomecánica de las flexiones, especialización deportiva, adaptación neuromuscular, electromiografía (EMG), análisis cinemático y cinético.

Introduction

The push-up is one of the most fundamental and universally applied upper-body exercises in athletic training, physical education, and performance assessment. Its scientific relevance extends beyond simplicity, as it simultaneously challenges upper-limb force production, trunk stabilization, intermuscular coordination, and force transmission within a closed kinetic chain (Jeffries et al., 2022; Kowalski et al., 2022). Unlike isolated resistance exercises, the push-up requires coordinated multi-joint action across the shoulder, elbow, wrist, and trunk, making it particularly sensitive to deficits in postural control, scapular stability, and neuromuscular synchronization (Gouvali & Boudolos, 2005). Biomechanically, the push-up reproduces horizontal pushing mechanics that are functionally transferable to sport-specific actions such as aquatic propulsion, blocking and screening in basketball, sprint-start support, and apparatus-based gymnastics skills (Strang et al., 2009; Calatayud et al., 2015). Consequently, the push-up is increasingly recognized not merely as a conditioning drill, but as a functional probe of integrated neuromuscular performance and movement quality.

From a neuromechanical perspective, push-up execution depends on the synergistic activation of the pectoralis major, anterior deltoid, and triceps brachii for force generation, combined with co-activation of the rectus abdominis, obliques, and erector spinae to stabilize the kinetic chain (Kowalski et al., 2022). Variations in this coordination directly influence joint loading, movement efficiency, and mechanical stability, which explains why the push-up is widely implemented in military testing, rehabilitation screening, and athlete monitoring protocols (Jeffries et al., 2022; Strang et al., 2009).

Despite its widespread use, the biomechanical expression of the push-up is not uniform across athletic populations. According to the principle of training specificity, long-term exposure to distinct sport constraints reshapes neuromuscular control strategies, joint coordination patterns, and muscle recruitment hierarchies (Wang, 2012; Glazier & Mehdizadeh, 2019). These adaptations form a sport-specific neuromuscular “engram,” representing the nervous system’s optimized response to repetitive mechanical demands. For example, gymnasts are chronically exposed to closed-chain loading that prioritizes trunk rigidity and joint stiffness, whereas swimmers develop increased shoulder excursion and propulsion-oriented muscle activation, and power-based athletes such as sprinters and basketball players emphasize rapid force generation and high rates of force development (Zhang et al., 2024; Suchomel et al., 2016; Chiu, 2018). Whether these sport-specific motor solutions persist during non-sport-specific tasks such as the push-up remains a fundamental question in applied biomechanics.

Previous push-up research has examined how technique modifications influence mechanical outcomes. Studies focusing on hand width and hand placement have demonstrated that narrow-grip push-ups significantly increase triceps brachii activation and elbow joint loading, whereas wider hand positions shift demand toward the pectoralis major and anterior deltoid (Aalto, 2020). Fatigue-based investigations further report that progressive exhaustion increases trunk angular variability and shoulder joint stress, potentially elevating injury risk (Bruce et al., 2023). However, these studies predominantly involved untrained or recreational participants, limiting their applicability to athletes with long-term sport-specific neuromuscular adaptations.

Parallel research on sport specialization provides compelling evidence that chronic training reshapes fundamental movement coordination. Quantitative analyses have shown that gymnasts exhibit significantly lower trunk angular displacement (reductions of 30–45%) and higher co-activation indices compared with non-gymnasts (Zhang et al., 2024), while power athletes demonstrate RFD values exceeding endurance-trained counterparts by more than 40% (Suchomel et al., 2016). Basketball players have been shown to generate higher joint moments during landing tasks than volleyball players (Noakes et al., 2011), and triple jumpers exhibit unique hip–knee–ankle coordination patterns during ground contact (Glazier & Mehdizadeh, 2019). Notably, the overwhelming majority of these investigations focus on lower-limb mechanics, leaving upper-limb and trunk-dominant movements such as the push-up markedly underexplored.

Taken together, existing literature suggests that (i) trained athletes from different sports are rarely compared during standardized upper-body closed-chain tasks (Prokopy et al., 2008); (ii) most push-up studies rely on isolated performance or EMG indicators rather than integrated kinematic–kinetic–EMG analyses (Dhahbi et al., 2022) and (iii) the neuromuscular mechanisms underlying sport-specific differentiation in upper-body movement remain insufficiently understood (Zemková & Zapletalová, 2022). Addressing these limitations is essential to clarify how deeply sport specialization penetrates general motor control strategies.

Accordingly, the present study investigates push-up biomechanics in athletes from four contrasting sport specializations gymnastics, swimming, track and field (sprinting), and basketball representing stability-dominant, mobility-dominant, and power-dominant training profiles. By integrating three-dimensional kinematics, kinetics, and electromyography, this study seeks to identify whether sport-specific neuromuscular adaptations manifest during a standardized, non-sport-specific task.

Research Objectives and Hypotheses

The objective of this study was to compare kinematic, kinetic, and electromyographic characteristics of push-up performance among athletes from four sport specializations. Specifically, it was hypothesized that gymnasts would demonstrate superior trunk–pelvic stability and higher core co-activation, swimmers would exhibit greater shoulder range of motion and reliance on prime movers, and power-oriented athletes (track and field sprinters and basketball players) would display higher peak forces and faster rates of force development.

Method

Research Design

This study employed a cross-sectional research design, appropriate for examining biomechanical differences in the push-up exercise among athletes from distinct sport specializations at a single point in time (Glazier & Mehdizadeh, 2019). This design allows for the identification of movement variations that may arise from long-term, specialization-specific training adaptations. While it provides an efficient framework for exploratory comparative analyses in applied biomechanics, it should be noted that causal inferences regarding training effects cannot be drawn.

Participants

Recruitment and Grouping

An a priori sample size estimation was conducted using G*Power software (version 3.1) based on the fixed-effects one-way ANOVA model, following the formula derived from Cohen's f effect size framework:

$f = \sigma m / \sigma$, where σm represents the standard deviation of group means and σ the pooled within-group standard deviation. An effect size of $f = 0.40$ (large effect), $\alpha = 0.05$, statistical power $(1-\beta) = 0.80$, and four independent groups were specified, resulting in a minimum required sample size of 76 participants. This procedure was selected over correlation-based or regression-based estimations because the primary objective of the study was the between-group comparison of biomechanical variables across discrete sport specializations, consistent with prior biomechanical comparative investigations.

To account for potential dropouts and unusable trials, 80 participants were finally recruited and completed all measurements.

Eighty male university student-athletes (age range 18–25 years) were equally allocated into four groups ($n = 20$ per group) according to their primary competitive sport specialization, defined as the sport in which the athlete had accumulated the highest training volume and competition exposure over the previous five years:

- Gymnastics Group: Artistic gymnasts specializing in apparatus and floor routines.
- Swimming Group: Freestyle or butterfly swimmers emphasizing upper-limb propulsion.
- Track and Field Group: Competitive sprinters in the 100 m and 200 m events.
- Basketball Group: Competitive basketball players occupying guard or forward positions.

The grouping strategy was grounded in the biomechanical principle of task-specific adaptation, whereby chronic exposure to distinct movement patterns and loading profiles is expected to result in unique neuromuscular and kinetic characteristics. Group identification was verified through official team registration records and direct confirmation from institutional coaches.

Inclusion Criteria

Participants were required to:

1. Be officially registered as competitive athletes by their respective national sport federations and actively competing at the inter-university or higher level. This classification does not imply identical competitive ranking across sports, but rather confirms that all participants were trained athletes performing within organized competitive systems.
2. Engage in systematic sport-specific training for at least five years, with a weekly volume ≥10 hours.
3. Be right-hand dominant, aged 18–25 years, and in good health.
4. Provide written informed consent after a full explanation of procedures and potential risks.

Exclusion Criteria

Participants were excluded if they:

1. Sustained upper-limb or lower-back injuries within the past six months.
2. Had chronic musculoskeletal disorders affecting upper-limb movement.
3. Engaged in strenuous exercise within 24 hours before testing or displayed signs of fatigue.

Participant Characteristics

Descriptive anthropometric and training information (age, height, weight, training years) were collected and are summarized in Table 1. Reporting these characteristics ensures transparency and allows for interpretation of inter-group differences.

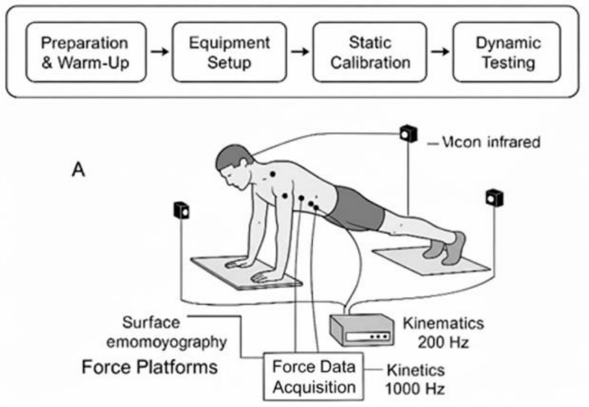
Experimental Procedure

All experimental procedures were conducted in a controlled biomechanics laboratory (ambient temperature 22–24°C). The study protocol was reviewed and approved by the Institutional Research Ethics Committee of Mahasarakham University (Thailand). All procedures conformed to the principles of the Declaration of Helsinki.

The experimental workflow comprised four sequential phases:

1. Preparation and standardized warm-up
2. Equipment setup and marker/electrode placement
3. Static calibration for model generation
4. Dynamic testing with synchronized motion capture, force, and EMG data acquisition

Figure 1. The spatial arrangement of force platforms, reflective markers, and the Vicon infrared camera system.



Preparation and Warm-Up

Participants received a standardized briefing and signed informed consent. Tight-fitting athletic attire was worn to facilitate marker placement. The 10-minute warm-up included:

- 5 minutes of light treadmill jogging,
- Dynamic stretching (arm circles, chest expansions, arm swings, torso rotations, lateral bends),
- 5 bodyweight push-ups for muscle activation.

Equipment Setup

Kinematic Markers

A modified Plug-in Gait full-body model was used, with 39 reflective markers (14 mm diameter) placed on anatomical landmarks, including the forehead, occiput, acromion processes, humeral epicondyles, radial/ulnar styloid processes, anterior and posterior superior iliac spines, femoral condyles, malleoli, heel, and second/third metatarsal heads (Niu et al., 2024).

Surface EMG Electrodes

After standard skin preparation (shaving, mild abrasion, and cleaning with 70% isopropyl alcohol), wireless Ag/AgCl surface electrodes (Delsys Trigno™, USA) were placed according to the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) recommendations as follows:

- Pectoralis Major (clavicular head): 2 cm inferior to the clavicle and medial to the axillary fold
- Anterior Deltoid: 2 cm distal to the acromion on the line to the deltoid tuberosity
- Triceps Brachii (long head): Midpoint between the acromion and olecranon on the posterior upper arm
- Rectus Abdominis: 3 cm lateral to the umbilicus
- Erector Spinae (L1): 3 cm lateral to the L1 spinous process

Electrode placement sites were selected to maximize signal specificity and minimize cross-talk, in accordance with international SENIAM guidelines. The reference electrode was positioned over the fibular head.

Static Calibration and Dynamic Testing

Participants performed a 3-second static calibration in an anatomical stance. For dynamic trials, the standardized push-up technique was as follows:

- Hands positioned shoulder-width apart, verified using biacromial distance.
- Palms placed symmetrically on the two force platforms, fingers oriented forward.
- Feet aligned parallel, shoulder-width apart, with the body forming a straight line from head to heels.
- The descending phase was performed until 90° elbow flexion was reached, confirmed in real time via motion capture.
- No trunk sagging, hip piking, or asymmetric loading was permitted. Trials violating these criteria were discarded and repeated.

Each participant completed three valid repetitions paced at 60 bpm, with a 2-minute passive recovery between trials.

Data Acquisition

Three synchronized systems captured kinematic, kinetic, and EMG data:

- Kinematics: 10-camera infrared motion capture system (Vicon Nexus, Vicon Motion Systems Ltd) at 200 Hz; spatial accuracy <0.5 mm.

- Kinetics: Two force platforms (Kistler 9286AA, Switzerland) measured vertical ground reaction forces under each hand at 1000 Hz, synchronized with motion capture.
- Surface EMG: Wireless Delsys Trigno™ Avanti system (USA), sampled at 2000 Hz, band-pass filtered 20–450 Hz, common-mode rejection ratio >100 dB. Built-in accelerometers assisted in identifying movement phases.

Kinematic (200 Hz), kinetic (1000 Hz), and EMG (2000 Hz) data were collected simultaneously. All systems were hardware-synchronized through the Vicon Nexus synchronization unit using a common digital trigger signal, ensuring temporal alignment at the millisecond level across all devices. Synchronization accuracy was verified through pre-test impulse trials on the force plates.

Filtering cutoffs were chosen based on prior literature to minimize noise while preserving signal fidelity (Alcan & Zinnuroğlu, 2023).

Data Processing

Data were processed using Visual3D (C-Motion, USA) and MATLAB (MathWorks, USA):

- Kinematic Data: Filtered with a 4th-order zero-lag Butterworth filter at 10 Hz.
- Kinetic Data: Filtered with a 4th-order zero-lag Butterworth filter at 50 Hz.
- EMG Data: Band-pass filtered (20–450 Hz), full-wave rectified, and smoothed using a 100 ms RMS window. EMG signals were normalized to post-trial MVIC, following standard procedures while considering potential fatigue effects (Powell et al., 2018).

Dependent Variables

All variables were derived from a complete push-up cycle (elbow-extended to return). The mean of three trials was used for analysis.

Kinematic Parameters:

- Joint Range of Motion: Shoulder flexion/extension, horizontal abduction/adduction; minimum elbow flexion.
- Trunk Stability: Standard deviation of pelvic and thoracic angles in frontal and sagittal planes.
- Movement Tempo: Ratio of concentric to eccentric phase duration.

Kinetic Parameters:

- Peak Force: Maximum vertical GRF across both hands.
- Mean Force: Average vertical GRF throughout the movement.
- Rate of Force Development (RFD): Slope of GRF increase during the first 50 ms of the concentric phase.

All biomechanical variables were extracted from three complete push-up repetitions, and the mean value across the three valid trials was used for all statistical analyses. Range of motion, force variables, and EMG amplitudes were therefore not derived from a single repetition, but from the average across the entire repeated task to improve measurement reliability.

Electromyographic Parameters

- Activation Intensity: Integrated EMG (iEMG) during concentric and eccentric phases, normalized to %MVIC.
- Activation Timing: EMG onset defined as amplitude exceeding resting mean by 3 SDs.
- Co-Activation Index: Calculated for the Pectoralis Major–Anterior Deltoid pair during key phases (100 ms before and after 90° elbow flexion) using normalized EMG amplitudes. Only one pair was analyzed due to electrode limitations.

Maximum voluntary isometric contractions (MVIC) were obtained for each recorded muscle prior to dynamic testing. Participants performed two 5-second maximal isometric contractions per muscle against standardized manual resistance, with a 60-second rest between trials. The highest RMS value recorded over a 1-second window was defined as MVIC and used for normalization. All EMG amplitudes during push-up trials were subsequently expressed as a percentage of the respective MVIC.

Statistical Analysis

All statistical analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA), with the level of statistical significance set a priori at $\alpha = 0.05$.

Descriptive statistics were calculated for all variables and are reported as means ± standard deviations. Fundamental anthropometric and training characteristics included age (years), body height (cm), body mass (kg), and training experience (years). Body height was measured using a wall-mounted stadiometer (Seca 213, Germany), body mass using a digital scale (Tanita BC-418, Japan), and training experience was obtained from verified institutional training records.

Prior to inferential analysis, assumption testing was conducted separately within each sport specialization group. Normality of all dependent variables was assessed using the Shapiro–Wilk test applied at the group level, while homogeneity of variance was examined using Levene's test. All primary biomechanical variables demonstrated acceptable normal distributions within groups ($P > 0.05$), supporting the use of parametric statistical procedures. Multivariate normality was additionally considered before performing MANOVA.Basic anthropometric and training characteristics: One-way ANOVA.

Group comparisons were conducted as follows:

a. Basic anthropometric and training characteristics were compared using one-way analysis of variance (ANOVA).

b. Overall biomechanical differences across sport specializations were examined using one-way multivariate analysis of variance (MANOVA) for kinematic, kinetic, and electromyographic variables.

c. When MANOVA results were statistically significant, follow-up univariate one-way ANOVAs were performed, with Tukey's honestly significant difference (HSD) test applied for post-hoc pairwise comparisons, adjusted for multiple testing.

Given that kinetic variables were normalized to body mass ($N \cdot kg^{-1}$), the use of ANCOVA with body mass as a covariate was deemed redundant. Accordingly, kinetic comparisons were reanalyzed using one-way ANOVA on normalized variables, ensuring statistical appropriateness and conceptual consistency. The results and interpretations remained unchanged in direction and magnitude, indicating that observed group differences reflect neuromechanical characteristics rather than anthropometric confounding.

Effect sizes were calculated and reported as partial eta squared (η^2) alongside p-values to indicate the magnitude and practical relevance of observed effects. This hierarchical analytical framework was selected to provide a statistically rigorous and interpretable comparison of sport-specific biomechanical patterns during push-up performance.

Results

This section presents the findings from kinematic, kinetic, and electromyographic (EMG) analyses during standardized push-up trials among university student-athletes from four sport specializations. Data are reported objectively, with statistical outcomes summarized in tables.

Participant Characteristics

Descriptive anthropometric and training variables, including age, body height, body mass, and years of formal training, were recorded for all participants using standardized measurement procedures. These characteristics are presented descriptively in Table 1 to provide an overview of the sample composition.

Table 1. Participants Characteristics

Group	N	Age (years)	Height (cm)	Weight (kg)	Training Years (years)
Gymnastics	20	20.4 ± 1.2	165.3 ± 4.5	58.6 ± 3.8	8.5 ± 1.8
Swimming	20	20.8 ± 1.1	180.2 ± 3.9	73.5 ± 4.2	9.1 ± 2.0
Track & Field	20	20.5 ± 1.0	177.6 ± 4.1	70.8 ± 3.9	8.3 ± 1.7
Basketball	20	20.7 ± 1.3	188.5 ± 5.1	82.4 ± 5.6	8.8 ± 1.9

F-value	-	0.45	85.32*	92.17*	0.68
P-value	-	0.72	<0.001	<0.001	0.57

Note: indicates P<0.05, statistically significant difference.

As shown in Table 1, there were no significant differences among the four groups in age (F=0.45, P=0.72) and training years (F=0.68, P=0.57), confirming comparability in sports experience. However, significant differences were observed in height (F=85.32, P<0.001) and weight (F=92.17, P<0.001). Post-hoc Tukey tests indicated that gymnasts were significantly shorter and lighter than the other groups (P<0.001), while basketball players were significantly taller and heavier (P<0.001). These anthropometric variations reflect sport-specific morphological adaptations, which must be considered in interpreting kinetic outcomes.

Kinematic, Kinetic, and Electromyographic (EMG) Results:

Table 2. Integrated Kinematic, Kinetic, and Electromyographic Parameters During Push-Up Performance by Sport Specialization (Mean ± SD)

Domain	Parameter	Gymnastics	Swimming	Track & Field	Basketball	F (df = 3,76)	p-value	η^2
Kinematic	Shoulder Horizontal Abduction (°)	35.2 ± 3.1^{a}	64.8 ± 4.2^{c}	44.5 ± 3.8^{b}	49.8 ± 3.5^{b}	15.43	<0.001	0.38
	Trunk Stability Index (°SD)	12.3 ± 2.1^{a}	27.9 ± 3.5^{c}	17.8 ± 2.8^{b}	22.1 ± 3.2^{b}	8.92	<0.001	0.26
	Pelvic Stability Index (°SD)	8.5 ± 1.8^{a}	19.2 ± 2.9^{c}	12.4 ± 2.2^{b}	15.7 ± 2.5^{b}	6.35	<0.01	0.24
	Concentric Phase Time (s)	2.1 ± 0.3^{b}	2.0 ± 0.2^{b}	1.4 ± 0.2^{a}	1.5 ± 0.3^{a}	10.67	<0.001	0.30
Kinetic	Relative Peak Force (N·kg^{-1})	1.45 ± 0.15^{b}	1.21 ± 0.12^{a}	1.52 ± 0.16^{b}	1.38 ± 0.14^{b}	5.89	<0.01	0.19
	Rate of Force Development (N·s^{-1})	2850 ± 320^{a}	2630 ± 280^{a}	4520 ± 480^{c}	3980 ± 420^{b}	18.34	<0.001	0.42
	Force–Time Integral (N·s)	185 ± 22^{b}	162 ± 18^{a}	198 ± 24^{c}	192 ± 21^{b}	4.23	<0.05	0.14
EMG	Pectoralis Major (%MVIC)	85.2 ± 8.5^{b}	94.8 ± 9.2^{c}	79.8 ± 7.9^{a}	75.3 ± 7.5^{a}	9.76	<0.001	0.28
	Anterior Deltoid (%MVIC)	80.1 ± 7.8^{b}	84.9 ± 8.3^{c}	74.7 ± 7.4^{a}	79.8 ± 7.9^{b}	4.12	<0.05	0.14
	Triceps Brachii (%MVIC)	74.8 ± 7.2^{a}	69.5 ± 6.8^{a}	89.6 ± 8.9^{c}	84.7 ± 8.3^{b}	7.21	<0.01	0.22
	Core Muscles (%MVIC)	89.5 ± 8.8^{c}	64.8 ± 6.3^{a}	74.9 ± 7.3^{b}	69.7 ± 6.8^{a}	8.45	<0.001	0.25
	Co-activation Index (%)	94.8 ± 9.3^{c}	65.2 ± 6.4^{a}	75.1 ± 7.4^{b}	70.3 ± 6.9^{a}	12.54	<0.001	0.33

Note: Values are presented as mean ± SD. Different lowercase superscript letters (a, b, c) within the same row indicate statistically significant pairwise differences between sport groups based on Tukey's post-hoc multiple comparison test (p < 0.05). Groups sharing the same letter do not differ significantly. Effect sizes are reported as partial eta squared (η^2). %MVIC percentage of Maximum Voluntary Isometric Contraction.

Kinematic Results

A MANOVA indicated significant overall differences in joint kinematics across specializations (Wilks' $\Lambda=0.512$, $F(15,204)=4.72$, $p<0.001$, partial $\eta^2=0.26$).

A multivariate analysis of variance (MANOVA) revealed significant overall differences in joint kinematic variables across the four sport specializations (Wilks' $\Lambda = 0.512$, $F(15,204) = 4.72$, $p < 0.001$, partial $\eta^2 = 0.26$, indicating a large multivariate effect). Univariate post-hoc analyses demonstrated that shoulder horizontal abduction differed significantly between groups ($F(3,76) = 15.43$, $p < 0.001$, $\eta^2 = 0.38$), with swimmers exhibiting the greatest range and gymnasts the lowest. Trunk stability index also differed significantly ($F(3,76) = 8.92$, $p < 0.001$, $\eta^2 = 0.26$), with gymnasts displaying the lowest angular variability, indicative of superior postural control. Similarly, pelvic stability index showed significant group differences ($F(3,76) = 6.35$, $p < 0.01$, $\eta^2 = 0.24$).

Concentric phase duration differed significantly among groups ($F(3,76) = 10.67$, $p < 0.001$, $\eta^2 = 0.30$), with Track and Field and Basketball athletes demonstrating faster concentric actions than gymnasts and swimmers. No statistically significant differences were observed in shoulder flexion/extension or minimum elbow flexion ($p > 0.05$); however, effect sizes ranged from small to moderate ($\eta^2 = 0.06$–0.11), suggesting limited practical relevance of these nonsignificant findings.

Kinetic Results

A one-way analysis of covariance (ANCOVA), conducted as a supplementary analysis to account for residual inter-individual variability in body mass, revealed significant group differences in relative peak force, rate of force development (RFD), and force–time integral (Table 2). Although selected kinetic variables were normalized to body mass (N·kg^{-1}), ANCOVA was applied to verify whether group differences persisted after statistically controlling for remaining body mass effects, a procedure recommended when anthropometric disparities between groups are substantial.

Relative peak force differed significantly among groups ($F(3,75) = 5.89$, $p < 0.01$, partial $\eta^2 = 0.19$), with gymnasts and Track and Field athletes producing the highest normalized values. RFD exhibited a large group effect ($F(3,75) = 18.34$, $p < 0.001$, partial $\eta^2 = 0.42$), with Track and Field athletes demonstrating markedly faster force production than the remaining groups. Force–time integral also showed significant differences ($F(3,75) = 4.23$, $p < 0.05$, partial $\eta^2 = 0.14$).

Importantly, the pattern and statistical significance of group differences were consistent when analyses were performed using normalized variables alone, indicating that the observed effects reflect genuine neuromechanical differences rather than body-mass artifacts.

Gymnastics and Track & Field athletes generated higher relative peak forces, while RFD was greatest in Track & Field and Basketball athletes.

Electromyographic (EMG) Results

MANOVA revealed significant differences in muscle activation patterns among groups (Wilks' $\Lambda = 0.489$, $F(20,228) = 3.97$, $p < 0.001$, partial $\eta^2 = 0.26$). Pectoralis major activation differed significantly ($F(3,76) = 9.76$, $p < 0.001$, $\eta^2 = 0.28$), with swimmers exhibiting the highest activation. Triceps brachii showed the largest activation in Track and Field athletes ($F(3,76) = 7.21$, $p < 0.01$, $\eta^2 = 0.22$). Core muscle activation was greatest in gymnasts ($F(3,76) = 8.45$, $p < 0.001$, $\eta^2 = 0.25$). Co-activation indices also differed markedly ($F(3,76) = 12.54$, $p < 0.001$, $\eta^2 = 0.33$).

Discussion

This study aimed to examine whether long-term sport specialization leads to differentiated biomechanical strategies during a standardized closed-chain upper-body task, and to identify the kinematic, kinetic, and electromyographic mechanisms underlying these differences. In line with the stated objectives and hypotheses, the findings demonstrate that push-up execution is not a uniform motor task across athletic populations but instead reflects distinct neuromuscular solutions shaped by prolonged exposure to sport-specific mechanical constraints.

Consistent with Hypothesis 1, gymnasts exhibited significantly lower trunk and pelvic angular variability alongside elevated co-activation indices, indicating a stability-dominant control strategy. This pattern suggests an increased reliance on anticipatory postural control and joint stiffness regulation, mechanisms that are essential in gymnastics to maintain alignment during inverted and apparatus-based skills. The concurrent reduction in segmental variability and increase in co-activation supports the interpretation that gymnasts prioritize movement precision and intersegmental coupling over movement economy. These findings extend previous observations by Hart et al. (2024) and Mendez-Rebolledo et al. (2022) by demonstrating that such stabilization strategies are not task-specific but generalize to non-gymnastics movements, reinforcing the concept of neuromuscular transfer across motor tasks.

In accordance with Hypothesis 2, swimmers displayed the greatest shoulder horizontal abduction and the highest pectoralis major activation, reflecting a mobility- and prime-mover–dominant strategy. Biomechanically, this suggests that force generation during push-ups in swimmers is achieved through increased joint excursion and muscle activation rather than through enhanced proximal stabilization. This finding aligns with the functional demands of swimming, where propulsion efficiency depends on large shoulder ranges of motion and repetitive concentric activation. Importantly, the reduced trunk stability observed in swimmers indicates a redistribution of neuromuscular resources toward the glenohumeral complex, supporting the flexibility–stability trade-off previously reported in aquatic biomechanics (Struyf et al., 2017; Dai et al., 2025).

Support for Hypothesis 3 was evident in sprinters and basketball players, who demonstrated markedly higher rates of force development and shorter concentric phase durations. These characteristics indicate a neuromuscular system optimized for rapid force production through accelerated motor-unit recruitment and heightened neural drive, rather than sustained force output or postural stabilization. The similarity of these upper-limb kinetic profiles to those reported in lower-limb explosive tasks (Suchomel et al., 2016) suggests that force–time specialization operates systemically across the body, rather than being confined to sport-dominant limbs. The faster concentric actions further imply superior utilization of stretch–shortening cycle mechanisms, even in horizontally oriented pushing tasks.

Collectively, the integration of kinematic, kinetic, and EMG findings demonstrates that sport specialization shapes movement through coordinated adaptations across multiple biomechanical domains, rather than isolated changes in single variables. Gymnasts achieve performance through stabilization and co-activation, swimmers through mobility and muscle activation amplitude, and power athletes through rapid force modulation. This multi-level differentiation confirms that push-up performance reflects an interaction between neural control strategies, joint mechanics, and force–time characteristics, thereby validating the study’s central premise.

Briefly, from a practical standpoint, these differentiated profiles suggest that push-up analysis may provide insight into underlying neuromuscular strategies characteristic of specific sports. However, as the present study was not designed to test training efficacy or injury outcomes, such implications should be interpreted cautiously and remain exploratory. Similarly, while differences in trunk stability and force development may be theoretically relevant to injury mechanisms, the current data do not permit causal inference or direct injury-risk conclusions, and these considerations should therefore be addressed in future targeted investigations.

Several limitations warrant careful consideration when interpreting the findings. The cross-sectional design precludes causal conclusions regarding training-induced adaptation, and self-selection into sports may partially contribute to observed group differences. Although training experience was broadly comparable, uncontrolled variation in cumulative training load and intensity may have influenced neuromuscular expression, particularly in rate-dependent variables such as RFD. Additionally, surface EMG does not capture deep stabilizing musculature, potentially underrepresenting the role of segmental stabilizers. Finally, the absence of fatigue conditions limits ecological validity, as neuromuscular strategies may shift under sustained load.

Future research should adopt longitudinal and intervention-based designs to clarify the directionality and plasticity of these adaptations. Integrating high-density or intramuscular EMG with biomechanical modeling may further elucidate coordination strategies, while fatigue-based protocols could reveal how sport-specific control mechanisms degrade or persist under competitive stress.

Conclusions

This study provides a unified biomechanical comparison of push-up execution among university male student-athletes from four sport specializations (gymnastics, swimming, track and field, and basketball) using an integrated kinematic, kinetic, and electromyographic approach. The findings demonstrate that long-term sport-specific training reorganizes neuromuscular control strategies even in a fundamental closed-chain task, producing distinct movement “signatures” aligned with the technical and physiological constraints of each discipline. Gymnasts displayed a stability-dominant pattern characterized by high trunk–pelvic control and elevated co-activation; swimmers exhibited a flexibility-dominant pattern with large shoulder excursions and prime-mover reliance; and power-oriented athletes (sprinters and basketball players) showed a power-dominant profile marked by rapid force development and shorter concentric phases.

These results confirm that kinematic, kinetic, and EMG adaptations operate as an integrated neuromuscular system rather than as isolated features. From a practical standpoint, the identification of sport-specific push-up biomechanical profiles offers a valuable framework for individualized strength training, injury-risk screening, and talent development. In summary, the push-up serves as a sensitive functional probe of neuromuscular specialization, linking fundamental biomechanics with applied performance science in trained athletes.

Acknowledgements

The authors would like to thank everyone who helped in completing this research.

Financing

This research was self-financed by the authors.

References

Alcan, V., & Zinnuroğlu, M. (2023). Current developments in surface electromyography. Turkish journal of medical sciences, 53(5), 1019-1031. https://doi.org/10.55730/1300-0144.5667

Aquino, M., Petrizzo, J., Otto, R. M., & Wygand, J. (2022). The impact of fatigue on performance and biomechanical variables—A narrative review with prospective methodology. Biomechanics, 2(4), 513-524. https://doi.org/10.3390/biomechanics2040040

Aalto, A. (2020). Effect of ten weeks maximal eccentric and concentric resistance training on muscle force in physically active young men in isokinetic bench press. https://urn.fi/URN:NBN:fi:jyu-202006154168

Bedo, B., Cesar, G., Andrade, V., Moura, F. A., Vieira, L. H. P., Aquino, R., ... & Santiago, P. R. P. (2022). Landing mechanics of basketball and volleyball athletes: a kinematic approach. Human Movement, 23(1), 80-88. https://doi.org/10.5114/hm.2021.104189

Bruce, O. L., Ramsay, M., Kennedy, G., & Edwards, W. B. (2023). Lower-limb joint kinetics in jump rope skills performed by competitive athletes. Sports Biomechanics, 22(11), 1398-1411. https://doi.org/10.1080/14763141.2020.1801823

Chiu, L. Z. (2018). Biomechanical methods to quantify muscle effort during resistance exercise. The Journal of Strength & Conditioning Research, 32(2), 502-513. https://doi.org/10.1519/JSC.0000000000002330

Dai, J., Ding, Y., & Dai, Z. (2025). Influence of trunk strength on sprint performance in swimmers: a cross-sectional analysis of torque-velocity relationships. Frontiers in Physiology, 16, 1625283. https://doi.org/10.3389/fphys.2025.1625283

Dhahbi, W., Chaabene, H., Chaouachi, A., Padulo, J., Behm, D. G., Cochrane, J., ... & Chamari, K. (2022). Kinetic analysis of push-up exercises: a systematic review with practical recommendations. Sports biomechanics. https://doi.org/10.1080/14763141.2018.1512149

Giancotti, G. F., Fusco, A., Varalda, C., Capranica, L., & Cortis, C. (2018). Biomechanical analysis of suspension training push-up. The Journal of Strength & Conditioning Research, 32(3), 602-609. https://doi.org/10.1519/JSC.0000000000002035

Glazier, P. S., & Mehdizadeh, S. (2019). Challenging conventional paradigms in applied sports biomechanics research. Sports Medicine, 49(2), 171-176. https://doi.org/10.1007/s40279-018-1030-1

Gouvali, M. K., & Boudolos, K. (2005). Dynamic and electromyographical analysis in variants of push-up exercise. The Journal of Strength & Conditioning Research, 19(1), 146-151.

Hart, E., Bauer, A. S., & Bae, D. S. (2024). Common upper extremity gymnastics injuries and gymnastic specific return to play protocols. Journal of the Pediatric Orthopaedic Society of North America, 6, 100016. https://doi.org/10.1016/j.jposna.2024.100016

Jeffries, A. C., Marcora, S. M., Coutts, A. J., Wallace, L., McCall, A., & Impellizzeri, F. M. (2022). Development of a revised conceptual framework of physical training for use in research and practice. Sports Medicine, 52(4), 709-724. https://doi.org/10.1007/s40279-021-01551-5

Kowalski, K. L., Connelly, D. M., Jakobi, J. M., & Sadi, J. (2022). Shoulder electromyography activity during push-up variations: a scoping review. Shoulder & elbow, 14(3), 325-339. https://doi.org/10.1177/17585732211019373

Mendez-Rebolledo, G., Olcese-Farias, Y., & Brown-Villegas, D. (2022). Balance control in artistic gymnasts and its comparison under three training methods: a pilot trial. Human Movement, 23(2), 56-64. https://doi.org/10.5114/hm.2021.106167

Niu, Z., Lu, K., Xue, J., Qin, X., Wang, J., & Shao, L. (2024). From methods to applications: A review of deep 3d human motion capture. IEEE Transactions on Circuits and Systems for Video Technology, 34(11), 11340-11359. https://doi.org/10.1109/TCSVT.2024.3423411

Noakes, T. D. (2011). Time to move beyond a brainless exercise physiology: the evidence for complex regulation of human exercise performance. Applied physiology, nutrition, and metabolism, 36(1), 23-35. https://doi.org/10.1139/H10-082

Powell, C., Jensen, J., & Johnson, S. (2018). Functional performance measures used for return-to-sport criteria in youth following lower-extremity injury. Journal of Sport Rehabilitation, 27(6), 581-590. https://doi.org/10.1123/jsr.2017-0061

Prokopy, M. P., Ingersoll, C. D., Nordenschild, E., Katch, F. I., Gaesser, G. A., & Weltman, A. (2008). Closed-kinetic chain upper-body training improves throwing performance of NCAA Division I softball players. The Journal of Strength & Conditioning Research, 22(6), 1790-1798. https://doi.org/10.1519/JSC.0b013e318185f637

Strang, A. J., Berg, W. P., & Hieronymus, M. (2009). Fatigue-induced early onset of anticipatory postural adjustments in non-fatigued muscles: support for a centrally mediated adaptation. Experimental brain research, 197(3), 245-254. https://doi.org/10.1007/s00221-009-1908-0

Struyf, F., Tate, A., Kuppens, K., Feijen, S., & Michener, L. A. (2017). Musculoskeletal dysfunctions associated with swimmers' shoulder. British journal of sports medicine, 51(10), 775-780. https://doi.org/10.1136/bjsports-2016-096847

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. Sports medicine, 46(10), 1419-1449. https://doi.org/10.1007/s40279-016-0486-0

Wang, Q. (2012). Individualized medicine, health medicine, and constitutional theory in Chinese medicine. Frontiers of Medicine, 6(1), 1-7. https://doi.org/10.1007/s11684-012-0173-y

Yazdani, S., & Mirghaffari, Z. (2024). Effect of Core Stability Exercises on Shoulder Pain, Muscle Strength, and Range of Motion in Female Swimmers With Shoulder Impingement Syndrome. The Scientific Journal of Rehabilitation Medicine, 12(6), 1150-1161. https://doi.org/10.32598/SJRM.12.6.13

Yesılyaprak, S. S., Türksan, H. E., & Karabay, D. (2022). Effects of a progressive rehabilitation program on shoulder internal rotation range of motion, acromiohumeral distance, and pain in an adolescent female swimmer with subacromial pain (impingement) syndrome. International Journal of Disabilities Sports and Health Sciences, 5(1), 56-65. https://doi.org/10.33438/ijdshs.1041097

Yilli, S., & Turgut, E. (2025). Competitive swimming and shoulder adaptations: The role of stroke specialty in adolescent swimmers. Physical Therapy in Sport, 74, 1-8. https://doi.org/10.1016/j.ptsp.2025.04.008

Zemková, E., & Zapletalová, L. (2022). The role of neuromuscular control of postural and core stability in functional movement and athlete performance. Frontiers in physiology, 13, 796097. https://doi.org/10.3389/fphys.2022.796097

Zhang, Z., Chen, L., Qin, Z., He, J., Gao, C., Sun, J., ... & Li, D. (2024). Effects of functional correction training on movement patterns and physical fitness in male college students. PeerJ, 12, e16878. https://doi.org/10.7717/peerj.16878

Authors and translators' details:

Runping Wu	274651905@qq.com	Author/Translator
Chairat Choosakul	chairat.c@msu.ac.th	Author

Appendixes: Complete Measurement Tools and Scales

Appendix 1: Participant Information and Health Screening Questionnaire:

I. Basic Information

ID: _________

Name: _________

Sex: ☐ Male ☐ Female

Age: _________ years

Height: _________ cm

Weight: _________ kg

Sport Specialization: _________

Training Years: _________ years

Athlete Level: ☐ International Master ☐ Master ☐ Level 1 ☐ Level 2

Contact Number: _________

II. Health and Injury History Screening (Please check Yes or No)

In the past 6 months, have you experienced pain or injury in your shoulders, elbows, wrists, back, or neck that required you to stop training or seek medical attention?

☐ Yes ☐ No

If "Yes," please specify location and details: __________________

Have you been diagnosed with any chronic diseases (e.g., heart disease, hypertension, arthritis)?

☐ Yes ☐ No

Do you have any known muscular, skeletal, or neurological disorders?

☐ Yes ☐ No

Have you engaged in strenuous exercise or felt significant fatigue in the past 24 hours? ☐ Yes ☐ No

Are you right-hand dominant for most activities?

☐ Yes ☐ No

Participant Declaration: I have fully understood the purpose, procedures, and potential risks of this test and voluntarily participate in this study. I confirm that the information provided above is true.
Participant Signature: ______________
Date: ____/____/_____

Appendix 2: Standardized Testing Protocol Checklist:

Phase	Step	Responsible Person	Check (✓)	Notes
Preparation	1. Explain procedure to participant, obtain informed consent	Principal Investigator	☐	
	2. Participant changes into tight-fitting athletic wear	Participant	☐	
	3. Perform 10-min standardized warm-up	PI/Participant	☐	5 min jog, 5 min dynamic stretching
Equipment Setup	4. Skin preparation (shave, abrade, clean with alcohol)	Experimenter	☐	Target muscle areas

	5. Apply surface EMG electrodes	Experimenter	☐	Order: Pect. Major, Ant. Deltoid, Triceps, Rectus Abd., Erector Spinae
	6. Apply reflective markers	Experimenter	☐	According to Plug-in Gait model
Data Collection	7. System calibration and synchronization	Experimenter	☐	Check all device signals
	8. Collect static calibration trial	Experimenter/Participant	☐	Anatomical stance for 3 sec
	9. Participant positioning, adjust push-up start posture	PI	☐	Hands shoulder-width, body straight
	10. Metronome rhythm familiarization (60 bpm)	Participant	☐	Practice 1-2 repetitions
	11. Formal testing, collect 3 valid trials	Experimenter	☐	2 min rest between trials
	12. Perform Maximal Voluntary Isometric Contraction tests	Experimenter/Participant	☐	For EMG normalization
Completion	13. Data saving and backup	Experimenter	☐	
	14. Remove equipment, thank participant	Experimenter	☐	

Appendix 3: Biomechanical Raw Data Recording Sheet (Example)

Parameter Category	Specific Parameter	Trial 1	Trial 2	Trial 3	Average	Unit
Kinematics	Shoulder Horizontal Abd. Angle (Peak)					°
	Elbow Min Angle					°
	Trunk Tilt Variation (SD)					°
	Pelvic Tilt Variation (SD)					°
	Concentric Phase Time					s
	Eccentric Phase Time					s
Kinetics	Vertical GRF Peak					N
	Relative Peak Force (Peak Force/BW)					N/kg
	Rate of Force Development (0-50ms)					N/s
EMG	Pectoralis Major (%MVIC)					%
	Anterior Deltoid (%MVIC)					%
	Triceps Brachii (%MVIC)					%
	Rectus Abdominis (%MVIC)					%
	Erector Spinae (%MVIC)					%
	Shoulder Co-activation Index					-

Data Processor: ____________

Participant ID: ___ Specialization: _______ Test Date: _______

Appendix 4: Maximal Voluntary Isometric Contraction (MVIC) Testing Protocol:

Used to normalize EMG signals from the push-up to %MVIC. Each action involves holding a maximal isometric contraction for 3-5 seconds, repeated 3 times, with 60-second rest intervals.

Pectoralis Major

Posture: Seated, shoulder abducted 90° and flexed 90°, elbow extended.

Resistance: Applied at the wrist, instruct participant to perform horizontal adduction.

Stabilization: Stabilize the shoulder girdle and trunk to prevent compensation.

Anterior Deltoid

Posture: Seated, shoulder flexed 90°, elbow extended.

Resistance: Applied downward on the distal arm, instruct participant to resist and maintain position.

Triceps Brachii

Posture: Prone, shoulder flexed 90°, elbow flexed 90°.

Resistance: Applied on the distal forearm, instruct participant to perform elbow extension.

Rectus Abdominis

Posture: Supine, hips and knees flexed to 90°.

Resistance: Applied against the sternum, instruct participant to perform a crunch and resist the force.

Erector Spinae

Posture: Prone, torso suspended over the edge of a plinth.

Resistance: Applied over the thoracic region, instruct participant to perform trunk extension and resist the force.

Recording: The average EMG amplitude over the middle 3 seconds of each MVIC trial is taken as the 100% MVIC reference value for that muscle.

Appendix 5: Data Quality Control Standards:

To ensure data validity, the following exclusion criteria were applied during data processing:

Movement Standardization:

Failure to fully extend elbows before initiating the next repetition.

Descent depth not reaching 90° elbow flexion.

Obvious trunk sagging (lordosis) or arching (kyphosis).

Movement rhythm deviating from the metronome by more than ±10%.

Signal Quality:

Loss of kinematic marker trajectory for more than 10 consecutive frames.

EMG signals containing significant motion artifact or baseline drift that cannot be corrected by filtering.

Force platform signals showing significant noise or abnormal peaks.

Validity Determination:

For each participant, at least 2 of the 3 trials must meet the above criteria to be included in the final analysis.

If only 1 trial is valid, additional testing is required.