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ORIGINAL RESEARCH

Effects of hand positions on neuromuscular control strategies in closed-kinetic-chain push-ups

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Abstract

Background: The push-up is a widely utilized closed kinetic chain exercise for upper body strength training, characterized by its versatility in hand positions. To elucidate the mechanisms underlying push-ups performed with varying hand positions, numerous studies have investigated differences in individual joint and muscle variables between these variations and standard push-ups. However, the underlying multi-joint neuromuscular control strategies remain unclear. This study aims to identify different neuromuscular control strategies by comparing muscle synergies across four push-up variations with standard push-ups. **Methods**: Thirteen male fitness enthusiasts participated in this study, performing five push-ups each with various hand positions: standard push-up (SP), wide grip push-up (WGP), narrow grip push-up (NGP), internally rotated push-up (IRP) and externally rotated push-up (ERP). Electromyographic (EMG) activity of ten major muscles in the dominant right upper limb was recorded. Muscle synergies were extracted using non-negative matrix factorization. **Results**: All push-up variations can be decomposed into two muscle synergies. More differences were seen in Synergy 1 compared to SP: WGP had higher posterior deltoid ($p = 0.001$, $d = -1.571$), NGP had higher triceps brachii ($p < 0.001$, $d = -1.816$) and upper trapezius ($p < 0.001$, $d = -1.843$), and ERP had lower flexor carpi ulnaris ($p = 0.005$, $d = 1.437$) and extensor carpi radialis ($p = 0.011$, $d = 1.346$) but higher biceps brachii ($p = 0.002$, $d = -0.858$) muscle weights. Synergy 2 showed higher similarity across variations. **Conclusions**: Hand position variations do not alter the number of muscle synergies but modify their patterns. More differences occur in the centrifugal to nadir phase (Synergy 1). Therefore, a greater focus of attention on the centrifugal phase may be more effective in achieving the training effect of each type of push-up.

Keywords

Muscle synergy; Strength training; Biomechanics; Non-negative matrix factorization

1. Introduction

Push-ups are a widely used and easy-to-perform method of closed kinetic chain (CKC) upper body strength training [1, 2], effective in exercising the muscles of the shoulders and arms [3]. The versatility of the push-up allows for a variety of hand positions [1, 4, 5]. To elucidate the mechanisms underlying push-ups performed with varying hand positions, previous studies examining the upper limb dynamics of push-ups with different hand distances and the degree of electromyography (EMG) activation of muscles have concluded that standard push-up (SP) produce greater elbow torque [6]. However, narrower grip push-up activate the triceps brachii (TB) and pectoralis major (PM) muscles more [5], and wider grip push-up put more stress on the medial aspect of the hand [7]. Additionally, research suggests that push-ups with internal palm rotation put more stress on the elbow joint compared to external rotation [8]. However, these studies have focused on how changes in hand position affect individual joints and muscles [5, 8], whereas push-ups involve multiple joint muscles in the upper limb [9], leaving the coordination between multi-joint muscles and the strategies for neuromuscular control unclear.

Muscle synergy can be explained as the central nervous system (CNS) streamlining movement generation by incorporating specific muscle activation patterns to optimize performance [10, 11]. EMG data from multiple muscles can be used to extract these synergies, reflecting the neuromuscular control strategies employed during movement [10, 12, 13]. Studies on shoulder muscle synergies for different arm movement directions in upper limb open kinetic chain (OKC) movements indicate that shoulder muscles can synergy well in basic movements [14]. Additionally, muscle synergy can elucidate the neuromuscular coordination involved in skilled athletes' throwing [15]. Studies of muscle synergy in various gestural movements have shown that muscle synergy can respond to different coordination patterns in different upper limb movements [16]. Muscle synergy has also been used to elucidate neuromuscular control strategies for lower limb CKC movements, such as changes of direction, revealing partial differences in muscle synergy for directional changes at different angles [17].

Existing studies have shown that the level of EMG activation of upper limb muscles varies according to hand position during the upper limb CKC exercise push-up [5]. These positional variations may affect multi-joint muscle synergies and have a more precise identification of the level of force in the neuromuscular control strategy reflected by muscle synergies compared to the degree of EMG activation [18]. Understanding the differences in neuromuscular control strategies for push-ups with different hand position variations could improve the use of push-up exercises and help develop more effective targeted training programs [19].

The SP is a widely used training method. Therefore, this study aimed to examine differences in muscle synergy across four hand position variations of push-ups (wide grip, narrow grip, internally rotated and externally rotated) compared to the SP, to identify differences in neuromuscular control strategies. We hypothesized that each push-up variation would exhibit a distinct muscle synergy pattern compared to standard push-ups. We believe that this study may provide new insights into optimizing push-up training methods.

2. Methods

2.1 Subjects

A total of 13 male right-handed college fitness enthusiasts (age, 21.1 $\pm$ 1.6 years; height, 175.25 $\pm$ 5.10 m; weight, 76.52 $\pm$ 5.14 kg; training experience, 5.1 $\pm$ 2.1 years; mean $\pm$ standard deviation) from the college of physical education participated in this experiment. These were asked to train in the gym no less than three times a week for no less than two hours each time, and to be able to easily complete various variations of push-ups. Participants were recruited between September and October 2024. Sample size calculation was conducted using G*Power 3.1.9.2 software (Heinrich Heine University Düsseldorf, Düsseldorf, NRW, Germany; one group of subjects, repeated measurements five times, f = 0.25, α = 0.05, β = 0.8, Corr = 0.7), indicating a minimum requirement of 13 participants. Participants had no upper extremity neuromuscular disorders, no history of upper extremity surgery, and no upper extremity injuries within the past six months. Each participant provided written informed consent after a detailed explanation of the testing protocol, possible risks involved, and their right to terminate participation at any time. All procedures were in accordance with the Declaration of Helsinki 1975, as revised in 2013, and were approved by the Jeonbuk University Ethics Committee (JBNU2022-04-008-002).

2.2 Experimental procedure

All experiments were conducted between 15:00–17:00 each day. Participants were asked to refrain from eating for two hours, consuming caffeine for eight hours, drinking alcohol for 48 hours, and did not perform upper body strength training for 48 hours prior to the experiment. All participants performed a standardized warm-up for ten minutes, consisting of full-body exercises and dynamic and static stretching of the upper extremities, at the end of which familiarisation exercises were performed on five push-up movement patterns. A five-minute rest period was then taken to allow body temperature and oxygen consumption to return to baseline levels before the push-up test [20]. Each participant was asked to perform SP and four variations of push-ups with different hand positions [8, 21]: widely grip push-up (WGP), narrow grip push-up (NGP), internally rotated push-up (IRP) and externally rotated push-up (ERP) (Fig. 1).

The position of the participant's hands of SP was defined as measured from the medial border of each hand, with a width equal to the distance between the crests of the shoulders, identified using a plumb line [5], with the hands placed under the shoulders in the starting position, characterized by full extension of the elbows. The distance between the two hands of WGP was approximately 150% of the shoulder width. The distance between the two hands of NGP was approximately 50% of the shoulder width. The palms were rotated 90° internally for IRP from the initial standard push-up position with the palms forward as a neutral reference position. The palms were rotated 90° externally for ERP from the initial standard push-up position with the arms at the participant's sides. The depth of all push-ups was uniformly less than 90 degrees of elbow flexion [22]. A metronome was used to control the tempo of the push-ups [1], as fast-cadenced push-ups have higher levels of strength and power output compared to slower cadences [23]. A cadence of two seconds for both concentric and eccentric movements has been shown to be effective in increasing upper body strength [24], so participants were asked to complete a push-up every four seconds. To avoid fatigue, each push-up was repeated five times, the type of push-up test was randomised, and a 90-second rest period was allowed between each type of push-up test.

2.3 Data collection

EMG data were collected using 10 wireless surface EMG sensors (Trigno Avanti, Delsys, Natick, MA, USA) equipped with dual differential rod (Ag) electrodes (2.7 $\times$ 3.7 cm) with a 10-channel 1200 Hz sampling frequency [25]. During push-ups, the sensors were placed on the flexor carpi ulnaris (FCU), extensor carpi radialis (ECR), biceps brachii (BB), triceps brachii (TB), anterior deltoid (AD), posterior deltoid (PD), pectoralis major (PM), serratus anterior (SA), upper trapezius (UT) and latissimus dorsi (LD) muscles of the right upper limb, and the locations of sensor placements were referenced to the Atlas of Muscle Innervation Regions. Skin preparation, including cleansing and shaving, was performed on the sensor placement sites prior to placement to reduce contact surface impedance between the skin and the electrodes [26]. The sensors were secured using kinesio tape [27]. Kinematic data from push-ups were acquired at an acquisition frequency of 120 Hz and synchronized with EMG data using a 13 infrared camera Motive 2.2.0 (OptiTrack, Natural Point, Inc., Corvallis, OR, USA) motion capture system with two reflective marker points affixed to the shoulder crest (to synchronize the time data) [28].

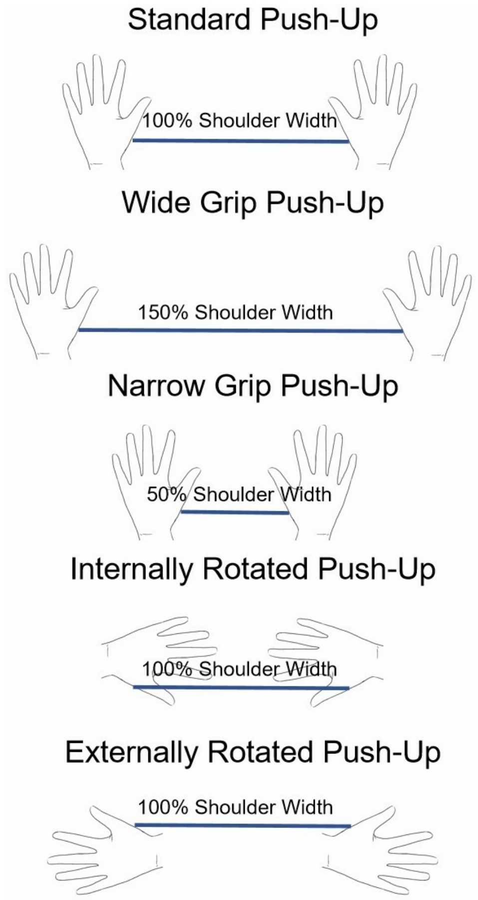


FIGURE 1. Push-ups in five hand positions.

2.4 Data processing

The acquired data was imported into Visual 3D software (C-Motion, Inc., Germantown, MD, USA) for processing, and the kinematics of the shoulder crest trajectory was filtered using low-pass filtering (6 Hz, Butterworth filter, 4th order) to truncate the stage of completion of each push-up according to the kinematic data of the shoulder crest [29]. Since there is a delay between EMG and muscle contraction, the EMG data were intercepted and exported with a delay of 30 ms between EMG and movement [30]. The exported EMG data were processed in MatlabR2021a (MathWorks, Natick, MA, USA), filtered using band-pass filtering (20–450 Hz, Butterworth filter, 4th order), followed by low-pass filtering (6 Hz, Butterworth filter, 4th order), full-wave rectification, extraction of the linear envelope and normalization to 101 data points [31, 32]. All EMG data were normalized to the maximum activation in all push-up movements, and the maximum activation level for each muscle was derived [33, 34]. To demonstrate retest performance, one of the two most relevant data sets was selected for each push-up for the muscle synergy decomposition [15]. This was finally collapsed to obtain the EMG matrix for each push-up.

To obtain the muscle synergies for each push-up, we used a non-negative matrix factorization (NMF) to decompose the EMG matrix and extract the upper limb muscle synergies for each push-up [35, 36].

$$\begin{aligned} EMG\,matrix &= M\ (synergy\,modules) \\ &\quad \times\ P\ (synergy\,primitive)\ +\ error \end{aligned}$$

The EMG matrix is a matrix consisting of m rows and n columns of processed raw EMG data (m = 10 is the number of muscles and n = 101 is the number of normalized time points). M is a matrix m rows and x columns (x is the number of muscle synergy) representing the muscle weights, *i.e.*, the synergy modules, P is a matrix x rows and n columns representing the temporal activation of synergy modules, *i.e.*, the synergy primitive, and the error is the initial difference between the EMG matrix and the difference between the reconstructed EMG matrix (M × P). The algorithm is based on iterative updating the initial random guesses of M and P, converging to a locally optimal matrix decomposition. To avoid local minima, it was repeated 20 times for each participant [14]. The least costly solution (*i.e.*, the squared error between the original and reconstructed EMG was minimized) was retained. The algorithm was used to decompose the EMG matrices of each of the five push-ups to obtain the synergy modules and synergy primitives.

To determine the number of synergy, we set the number of synergy to be analyzed iterative between 1 and 10, and then selected the synergy that had the lowest number of synergy and accounted for a coefficient of variation (VAF) >95% [18].

$$VAF = 1 - \frac{|EMG\,matrix - M \times P|^2}{|EMG\,matrix|^2}$$

In order to classify the synergy modules and synergy primitives for each push-up synergy effect, we set the number of synergy effects x to k using the k-means clustering algorithm [15, 17]. And considering that the k-means solution is affected by the number of initial prime clustering primes, it was repeated 50 times for different initial primes to reduce randomness. We also calculated the contour scores of all clustering results to evaluate the optimal clustering results, and selected the results with the highest contour scores to output the clustering synergy modules and their corresponding synergy primitives [15, 17].

2.5 Statistical analysis

Pearson's correlation coefficient was used to assess the similarity within-group and between-group for the five push-up synergy primitives ($0.00 < r < 0.20$ no similarity; $0.20 < r < 0.40$ weak similarity; $0.40 < r < 0.60$ moderate similarity; $0.60 < r < 0.80$ strong similarity and $0.80 < r < 1.00$ very strong similarity), with the significance set at $p < 0.05$. The cosine similarity (CS) test was used for the within-group and between-group similarity tests (the closer to 1 the higher the similarity) for the synergy modules [15, 33], defining CS >0.8 as similar [33]. Since this study focused on comparing the differences between the four variations of push-ups and SP, paired-samples *t*-tests were used to compare the differences between the weights of each muscle in the synergy module between the four push-ups and the standard push-ups, as well as the differences in the maximum muscle activation. All data analyses were performed in MatlabR2021a, and the normality of the data set was confirmed by the Shapiro-Wilk test ($p > 0.05$).

3. Results

3.1 Number of synergies

The VAF was calculated for each push-up with the number of synergies set from 1 to 10. When the number of synergies was set to 2, the average VAF for each push-up was greater than 0.95 (SP VAF = 0.970 ± 0.009, WGP VAF = 0.969 ± 0.014, NGP VAF = 0.954 ± 0.018, IRP VAF = 0.968 ± 0.011, ERP VAF = 0.952 ± 0.017), indicating that the neuromuscular control strategies for each push-up were well explained with this number of synergies (Fig. 2). Therefore, the number of synergies was set to 2.

3.2 Characterization of synergy primitives

The two synergy primitives peaked sequentially in the temporal order. A within-group correlation test of the push-ups for each synergy primitive showed that the within-group similarity for synergy primitive 1 was high, with all push-ups showing strong similarity ($r > 0.6$) (Fig. 3). For synergy primitive 2, all push-ups except ERP ($r = 0.468$) also exhibited strong similarity ($r > 0.6$). The between-group correlation test revealed moderate similarity for SP with NGP ($r1 = 0.507$, $r2 = 0.582$) and ERP ($r1 = 0.530$, $r2 = 0.550$), while WGP ($r1 = 0.669$, $r2 = 0.761$) and IRP ($r1 = 0.678$, $r2 = 0.796$) demonstrated strong similarity (Fig. 3).

3.3 Characterization of synergy module

The CS test for each type of push-up indicated that the within-group similarity for each synergy module was high (CS > 0.8) (Fig. 4). Between-group similarity showed low similarity between NGP and SP in synergy module 1 (CS = 0.768) (Fig. 4).

3.4 Muscle weights

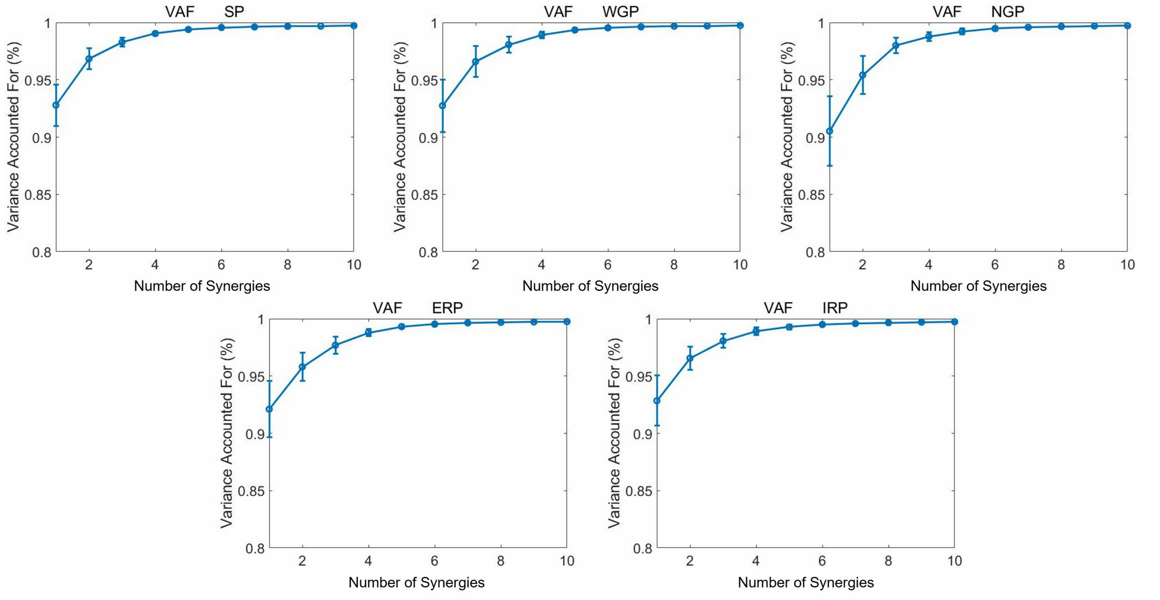
In synergy module 1, WGP exhibited higher PD ($p = 0.001$, $d = -1.571$) and lower PM ($p = 0.004$, $d = 1.286$) muscle weights compared to SP, NGP exhibited lower ECR ($p = 0.029$, $d = 1.070$) and BB ($p = 0.003$, $d = 1.593$) muscle weights, but higher TB ($p < 0.001$, $d = -1.816$) and UT ($p < 0.001$, $d = -1.843$) muscle weights. Moreover, IRP exhibited higher SA ($p = 0.019$, $d = -1.030$) muscle weights, and ERP exhibited lower FCU ($p = 0.005$, $d = 1.437$) and ECR ($p = 0.011$, $d = 1.346$) muscle weights, but higher BB ($p = 0.002$, $d = -0.858$) and UT ($p = 0.003$, $d = -1.518$) muscle weights (Fig. 5). In synergy module 2 compared to SP, WGP had lower AD ($p = 0.039$, $d = 1.027$) muscle weights, NGP similarly exhibited lower AD ($p = 0.044$, $d = 0.876$) muscle weights, IRP did not differ in the weights of the respective muscles, whereas ERP exhibited higher FCU ($p = 0.021$, $d = -1.034$), but lower TB ($p = 0.001$, $d = 1.732$) and PD ($p = 0.034$, $d = 0.970$) muscle weights (Fig. 5).

3.5 Muscle activation levels

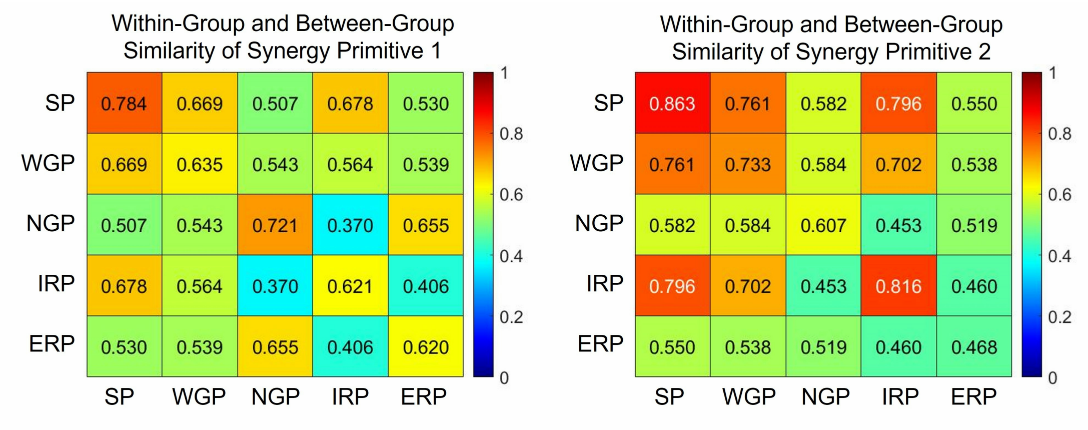
Comparing the four push-ups with the differences in the degree of activation of each muscle in the SP, the WGP demonstrated lower UT ($p = 0.032$, $d = 1.041$) muscle activation, the NGP demonstrated lower BB ($p = 0.031$, $d = 1.040$), but higher TB ($p = 0.012$, $d = -1.275$) and UT ($p < 0.001$, $d = -2.180$) muscle activation, IRP exhibited lower AD ($p = 0.019$, $d = 1.283$) muscle activation, while ERP exhibited lower FCU ($p = 0.026$, $d = 1.181$), higher BB ($p < 0.001$, $d = -3.026$), PM ($p = 0.002$, $d = -0.925$) and UT ($p = 0.004$, $d = -1.970$) muscle activation (Fig. 6).

4. Discussion

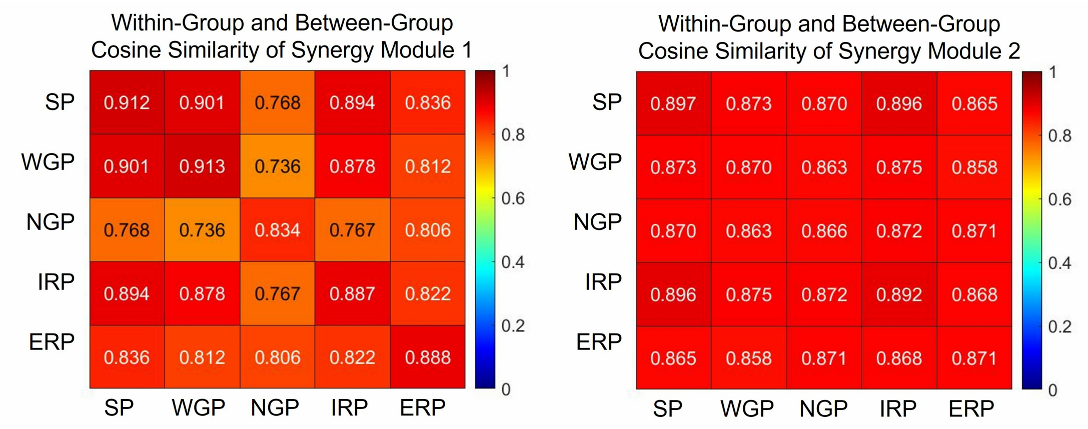
The purpose of this study was to compare the upper limb muscle synergies in four variations of push-ups with SP to investigate whether different neuromuscular control strategies are employed. The findings confirmed our hypothesis, revealing variations in muscle synergy patterns across the different push-up variations compared to the standard push-up. All push-up variations could be explained by two synergies, with peak activation occurring in the middle (during eccentric descent to the nadir) and late (during concentric contraction) phases of the push-up. These two synergies sequential activation suggests that push-ups employ a relatively simple neuromuscular control strategy [16]. The redundancy of the



F I G U R E 2. Mean VAF and standard deviation of the 13 participants from 5 push-ups with different number of synergies. VAF: variance accounted for; SP: standard push-up; WGP: widely grip push-up; NGP: narrow grip push-up; IRP: internally rotated push-up; ERP: externally rotated push-up.



F I G U R E 3. Within-group and between-group similarity of synergy primitives of the 13 participants from 5 push-ups. SP: standard push-up; WGP: widely grip push-up; NGP: narrow grip push-up; IRP: internally rotated push-up; ERP: externally rotated push-up.



F I G U R E 4. Within-group and between-group cosine similarity of synergy primitives of the 13 participants from 5 push-ups. SP: standard push-up; WGP: widely grip push-up; NGP: narrow grip push-up; IRP: internally rotated push-up; ERP: externally rotated push-up.

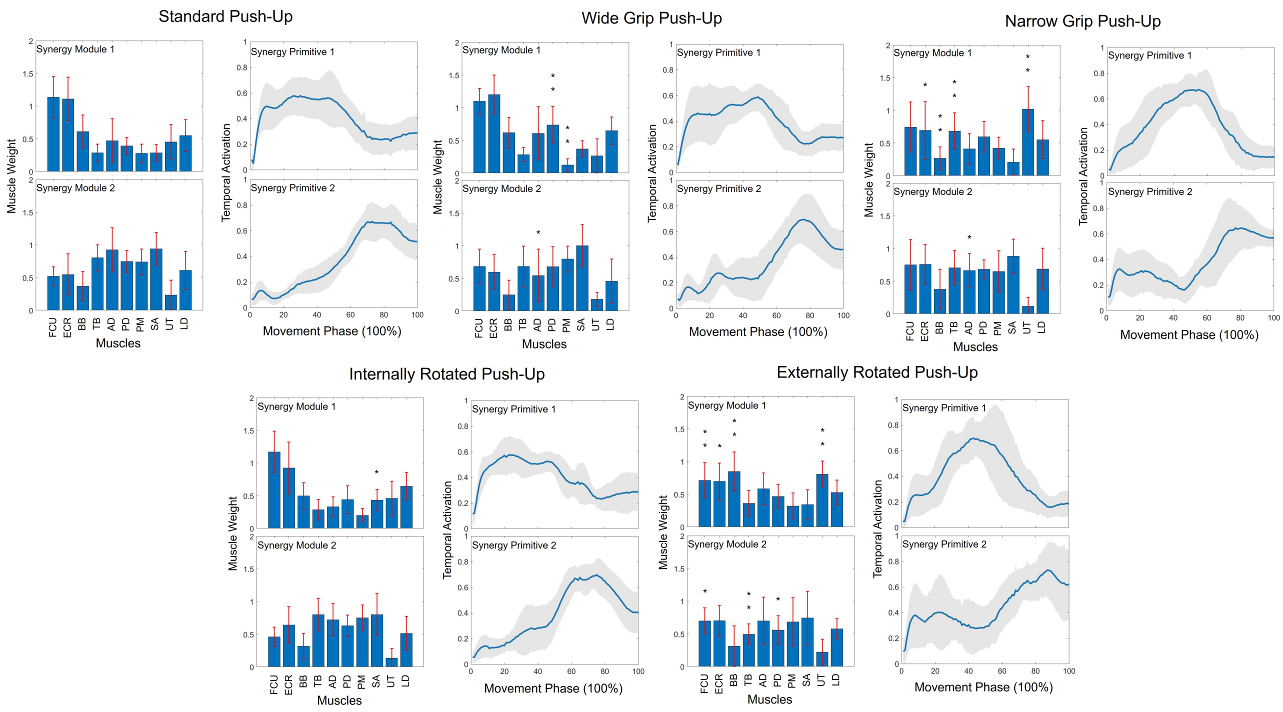


FIGURE 5. Synergy modules (M) and synergy primitives (P) of the 13 participants from 5 push-ups. FCU: flexor carpi ulnaris; ECR: extensor carpi radialis; BB: biceps brachii; TB: triceps brachii; AD: anterior deltoid; PD: posterior deltoid; PM: pectoralis major; SA: serratus anterior; UT: upper trapezius; LD: latissimus dorsi; * is significant ($p < 0.05$) and ** is highly significant ($p < 0.01$) compared to standard push-up. In the bar graph, the Y-axis is the weight of the muscle and the X-axis is the muscle name. In the line graph, the Y-axis represents the degree of activation of the module, and the X-axis represents the normalized 101 data points.

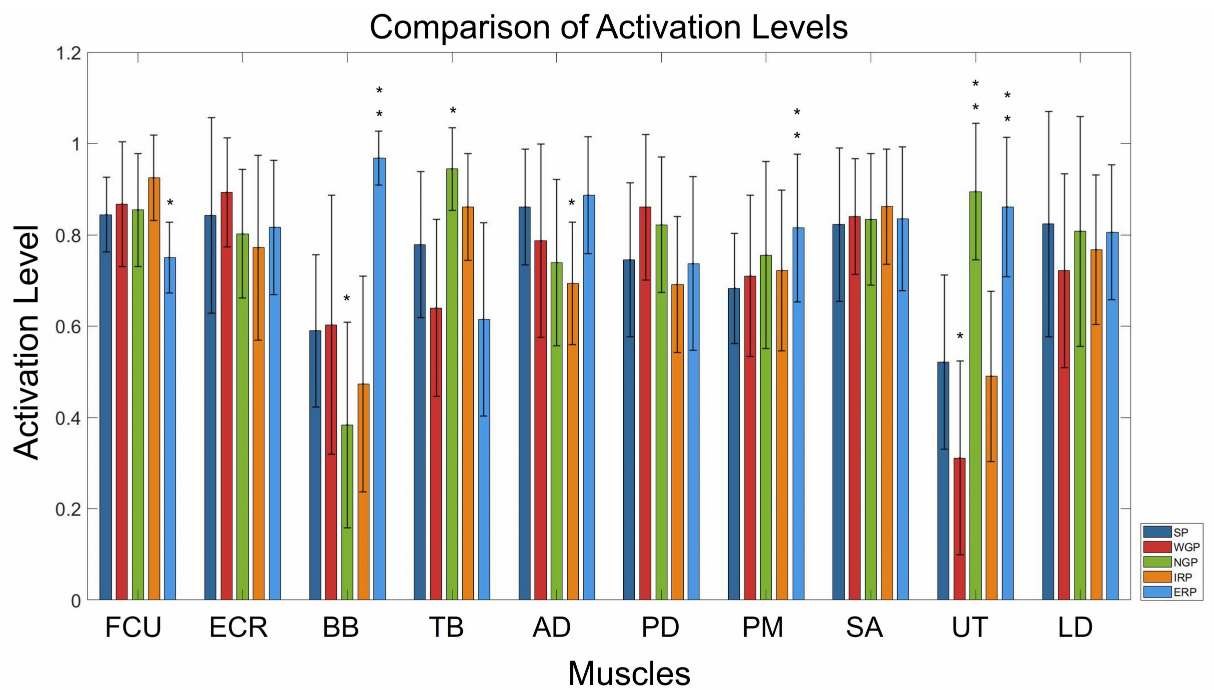


FIGURE 6. Comparison of activation levels for 5 push-ups in 13 participants. SP: standard push-up; WGP: widely grip push-up; NGP: narrow grip push-up; IRP: internally rotated push-up; ERP: externally rotated push-up; FCU: flexor carpi ulnaris; ECR: Extensor carpi radialis; BB: biceps brachii; TB: triceps brachii; AD: anterior deltoid; PD: posterior deltoid; PM: pectoralis major; SA: serratus anterior; UT: upper trapezius; LD: latissimus dorsi; * is significant ($p < 0.05$) and ** is highly significant ($p < 0.01$) compared to SP.

human musculoskeletal system allows the CNS to select the most effective motor solutions from a vast array of behavioral options. Consequently, many studies have aimed to identify the optimal parameters for upper limb motor control [37]. Research has also explored the computational mechanisms between CNS and muscle control in upper limb movements, such as throwing [15], shoulder movements [14] and gesture changes in upper limb muscle synergy [16, 18]. However, the acromioclavicular, sternoclavicular, glenohumeral and scapulothoracic joints of the upper limb are typically described as a kinetic chain [2, 38]. In contrast, push-ups are a CKC exercise with distal joint fixation, resulting in most movement occurring at the proximal joints [2, 38, 39]. This distal fixation reduces musculoskeletal redundancy, simplifying neuromuscular control during push-ups.

Previous studies have recommended WGP to enhance PM stimulation [5]. However, this study did not find a significant increase in PM muscle weights or maximal activation in WGP compared to SP. Interestingly, higher PM maximal activation was observed in ERP compared to SP. The primary functions of the PM muscles are shoulder flexion and adduction [40], with the distal attachment on the crest of the greater tuberosity of the humerus [41]. The humerus forms a smaller angle relative to the trunk in NGP and ERP compared to SP, WGP and IRP, resulting in shorter PM muscle length. Due to the muscle force-length relationship, shorter muscle lengths may recruit more motor units to generate the necessary tension [5]. This may explain the higher activation of PM in NGP and ERP. However, this study does not negate the training effects of WGP on PM. Muscle activation alone is insufficient to evaluate muscle condition, as activation at different muscle lengths cannot be directly compared [42]. Performing work at longer muscle lengths may lead to greater stimulus and faster fatigue [43]. Additionally, this study found increased UT muscle weights and maximal activation in NGP and ERP compared to SP. The distal attachment of the UT is on the lateral side of the clavicle [41], and humeral elevation involves scapular upward rotation, which elevates the lateral clavicle [44]. A wider hand position increases the humeral angle, reducing UT muscle length. Higher activation at longer muscle lengths in NGP and ERP suggests better training effects for the UT. However, excessive UT muscle activation may attempt to compensate for the fact that SA causes the scapula to rotate abnormally, disruption of the normal scapulohumeral rhythm, leading to abnormal scapular motion and potential impingement [45]. Assessing muscle activation in the context of scapular positioning is crucial, as the moment arms of shoulder muscles are not fixed but vary with thoracic-humeral posture [19, 46]. Changes in this posture can influence the biomechanical efficiency of muscle function, affecting both muscle activation and joint stress, which in turn affects the results of muscle coordination. High UT activation in NGP and ERP may be necessary to maintain shoulder joint stability. Conversely, the greater degree of scapular rotation in WGP and IRP increased PD activation in synergy module 1 of WGP. This change in muscle weights may reflect a neuromuscular adaptation to maintain shoulder stability during the eccentric phase, resulting in different training effects.

The present study found an increase in muscle weights and maximal activation in the synergy module 1 of the elbow extensor TB muscle during the NGP compared to the SP. Unlike the PM, the range of motion of the TB muscles was consistent because we specified a flexion target of 90 degrees at the elbow joint and controlled for completion time [42]. This result aligns with the higher TB activation observed in the NGP in the study by Archambault *et al*. [5] and supports previous recommendations for the NGP to enhance TB stimulation [47]. Additionally, the present study found a reduction in wrist muscle weights in the synergy module 1 of the NGP and ERP compared to the SP. Previous research has shown that wider hand-distance push-ups place more stress on the medial wrist joint and the lunate bone region [7], which may have led to higher synergy activation of the wrist muscles for wider push-ups. In ERP, we also found an increase in BB muscle weights in synergy module 1. There is a greater forward force on the body during both SP and ERP [8], but in SP, with the fingertips facing forward, this forward force can be resisted by the wrist flexor muscles. In contrast, when the hand is externally rotated and the elbow movement is in the sagittal plane, the forward force can only be resisted by compensating through the elbow flexors, which may account for the increased BB muscle weights in the ERP.

Push-ups are a common method of upper limb muscle rehabilitation [1], where the shoulder joint involved is one of the most complex musculoskeletal systems in the human body [14]. Almost any movement that occurs in the shoulder complex involves the coordination of many muscles that can guide and support the shoulder joint through a wide range of motion [14, 41]. Some muscles attached to the humerus are involved in stabilizing the proximal bones of the scapula or clavicle, and their activity can also produce movement of the humerus [40]. Different angles of the humerus during push-ups correspond to different humeral movements, impacting shoulder muscle synergy. The humeral angles in SP, WGP, and IRP are greater compared to NGP and ERP, which may lead to high activation of synergy primitives 1 in SP, WGP, and IRP from the beginning of push-ups. Different hand positions result in varying ground stress directions, leading to differences in elbow stress magnitude and humeral angle relative to the body [5–7]. Consequently, participants use different upper limb muscle synergies to complete the push-up. Although NGP and ERP have different hand positions, both have humeral positions in WGP and IRP closer to the body compared to SP, which may explain the similar synergies of NGP and ERP compared to SP, but relatively small compared to WGP and IRP. These differences in synergy primitives and modules appeared mostly in Synergy 1 (centrifugal to nadir phase). All four push-up variations had high similarity in synergy module 2 compared to SP, suggesting similar muscle synergy during the centripetal contraction of push-ups. Thus, hand position and humeral position differences due to hand position may be key to different muscle synergies in push-ups. Internal and external attention have been shown to influence the level of EMG activation during upper body training [48], and external attention may improve the training effect [49]. More external attention to control the centrifugal to nadir phase (Synergy 1) may better indicate the training effect of each type of push-up. Therefore, synergies can explain more of the neuromuscular control strategies of push-ups than simply comparing maximal muscle activation for various push-ups.

This study also has some limitations, the number of muscles selected was limited, the number of muscles can have an effect on the amount of muscle synergy [50]. EMG acquisition was performed using surface electrodes, which restricts data collection to superficial muscle groups. However, muscle is a complex system composed of multiple fascicles and muscle fibers, each with distinct discharge rates and histochemical properties. In the current synergy model, the smallest unit of analysis is the entire muscle [51], making it impossible to capture deeper or more nuanced patterns of synergy within the muscle itself. Additionally, only male participants were included, and results may not apply to females due to different body mass distributions. Furthermore, the sample size in this study was relatively small (n = 13), which may limit the generalizability of the findings.

5. Conclusions

This study reveals that the neuromuscular strategies for the upper limbs during various push-up variations can be explained by two distinct muscle synergies. The four push-up variations exhibit distinct neuromuscular control strategies compared to the standard push-up (SP). Coaches can select the most suitable upper limb training modality based on these variations and the athletes' specific needs. Furthermore, these differences were predominantly observed in in the centrifugal to nadir phase (Synergy 1). Enhanced control and a greater focus of attention on this phase are likely to result in more targeted training effects for the various push-up variations.

AVAILABILITY OF DATA AND MATERIALS

Data will be available on request to the corresponding authors.

AUTHOR CONTRIBUTIONS

PLF and YK—contributed equally to this work and share the first authorship; conceptualization, investigation, methodology, validation, formal analysis, writing-original draft, project administration. XT and TW—investigation, methodology. BRL and SK—conceptualization, methodology, resources, supervision, visualization, writing-original draft, writing-review. All authors read and approved the final version of the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study complies with the Declaration of Helsinki. The study protocol was explained to all participants, and they signed a formal informed consent form. The protocol of this study was approved by the Jeonbuk National University Institutional Review Board and performed in accordance with relevant guidelines/regulations (JBNU2022-04-008-002).

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CONFLICT OF INTEREST

Authors have no relationships or financial interests that might conflict with the work described in this study.

REFERENCES

[1] Ebben WP, Wurm B, VanderZanden TL, Spadavecchia ML, Durocher JJ, Bickham CT, *et al.* Kinetic analysis of several variations of push-ups. Journal of Strength and Conditioning Research. 2011; 25: 2891–2894.

[2] Herrington L, Waterman R, Smith L. Electromyographic analysis of shoulder muscles during press-up variations and progressions. Journal of Electromyography and Kinesiology. 2015; 25: 100–106.

[3] Sha Z, Dai B. The validity of using one force platform to quantify whole-body forces, velocities, and power during a plyometric push-up. BMC Sports Science, Medicine and Rehabilitation. 2021; 13: 103.

[4] Nichols IA, Szivak TK. Effects of different hand widths on plyometric push-up performance. Journal of Strength and Conditioning Research. 2021; 35: S80–S83.

[5] Cogley RM, Archambault TA, Fibeger JF, Koverman MM, Youdas JW, Hollman JH. Comparison of muscle activation using various hand positions during the push-up exercise. Journal of Strength and Conditioning Research. 2005; 19: 628–633.

[6] Donkers MJ, An KN, Chao EY, Morrey BF. Hand position affects elbow joint load during push-up exercise. Journal of Biomechanics. 1993; 26: 625–632.

[7] Chuckpaiwong B, Harnroongroj T. Palmar pressure distribution during push-up exercise. Scandinavian Journal of Medicine & Science in Sports. 2009; 50: 702–704.

[8] Arghadeh R, Alizadeh MH, Minoonejad H, Sheikhhoseini R, Asgari M, Jaitner T. Electromyography of shoulder muscles in individuals without scapular dyskinesis during closed kinetic chain exercises on stable and unstable surfaces: a systematic review and meta-analysis. Frontiers in Sports and Active Living. 2024; 6: 1385693.

[9] Allen CC, Dean KA, Jung AP, Petrella JK. Upper body muscular activation during variations of push-ups in healthy men. International Journal of Exercise Science. 2013; 6: 3.

[10] Cheung VCK, Seki K. Approaches to revealing the neural basis of muscle synergies: a review and a critique. Journal of Neurophysiology. 2021; 125: 1580–1597.

[11] Kerkman JN, Daffertshofer A, Gollo LL, Breakspear M, Boonstra TW. Network structure of the human musculoskeletal system shapes neural interactions on multiple time scales. Science Advances. 2018; 4: eaat0497.

[12] Cheung VC, d'Avella A, Bizzi E. Adjustments of motor pattern for load compensation via modulated activations of muscle synergies during natural behaviors. Journal of Neurophysiology. 2009; 101: 1235–1257.

[13] d'Avella A, Bizzi E. Shared and specific muscle synergies in natural motor behaviors. Proceedings of the National Academy of Sciences. 2005; 102: 3076–3081.

[14] Umehara J, Yagi M, Hirono T, Ueda Y, Ichihashi N. Quantification of muscle coordination underlying basic shoulder movements using muscle synergy extraction. Journal of Biomechanics. 2021; 120: 110358.

[15] Aoyama T, Ae K, Kohno Y. Interindividual differences in upper limb

muscle synergies during baseball throwing motion in male college baseball players. Journal of Biomechanics. 2022; 145: 111384.
[16] Chen X, Dong X, Feng Y, Jiao Y, Yu J, Song Y, *et al*. Muscle activation patterns and muscle synergies reflect different modes of coordination during upper extremity movement. Frontiers in Human Neuroscience. 2023; 16: 912440.
[17] Pan Z, Liu L, Li X, Ma Y. Characteristics of muscle synergy and anticipatory synergy adjustments strategy when cutting in different angles. Gait & Posture. 2024; 107: 114–120.
[18] Li Z, Zhao X, Wang Z, Xu R, Meng L, Ming D. A hierarchical classification of gestures under two force levels based on muscle synergy. Biomedical Signal Processing and Control. 2022; 77: 103695.
[19] Ho AJ, Cudlip AC, Ribeiro DC, Dickerson CR. Examining upper extremity muscle demand during selected push-up variants. Journal of Electromyography and Kinesiology. 2019; 44: 165–172.
[20] Li M, Meng X, Guan L, Kim Y, Kim S. Comparing the effects of static stretching alone and in combination with post-activation performance enhancement on squat jump performance at different knee starting angles. Journal of Sports Science and Medicine. 2023; 22: 769–777.
[21] Dhahbi W, Chaabene H, Chaouachi A, Padulo J, Behm DG, Cochrane J, *et al*. Kinetic analysis of push-up exercises: a systematic review with practical recommendations. Journal of Strength and Conditioning Research. 2022; 21: 1–40.
[22] Freeman S, Karpowicz A, Gray J, McGill S. Quantifying muscle patterns and spine load during various forms of the push-up. Medicine & Science in Sports & Exercise. 2006; 38: 570–577.
[23] LaChance PF, Hortobagyi T. Influence of cadence on muscular performance during push-up and pull-up exercise. Journal of Strength and Conditioning Research. 1994; 8: 76–79.
[24] Vossen JF, Kramer JE, Burke DG, Vossen DP. Comparison of dynamic push-up training and plyometric push-up training on upper-body power and strength. Journal of Strength and Conditioning Research. 2000; 14: 248–253.
[25] Guan L, Li K, Li H, Kim Y, Kim S. Effects of core muscle stability on kicking performance during the aerial phase of taekwondo wing kicks. Journal of Men's Health. 2024; 20: 138–148.
[26] Popesco T, Gardet Q, Bossard J, Maffiuletti NA, Place N. Centrally mediated responses to NMES are influenced by muscle group and stimulation parameters. Scientific Reports. 2024; 14: 24918.
[27] Hu Z, Zhang Y, Dong T, Dong M, Kim S, Kim Y. Gender differences in neuromuscular control during the preparation phase of single-leg landing task in badminton. Journal of Clinical Medicine. 2023; 12: 3296.
[28] Dong M, Lee J-H, Wang J, Xu Y, Wu C, Kim S. The contribution of upper or lower extremity of male athletes differs as distances of overhead volleyball pass increase. Journal of Men's Health. 2024; 20: 198–206.
[29] Qu Q, Wu C, Xu Y, Lu Y, Zhang J, Kim S. Effects of mobile phone task engagement on gait and dynamic stability during stair ascent and descent. Molecular & Cellular Biomechanics. 2024; 21: 243.
[30] Norman RW, Komi PV. Electromechanical delay in skeletal muscle under normal movement conditions. Acta Physiologica Scandinavica. 1979; 106: 241–248.
[31] Ferreira CL, Oliveira Barroso F, Torricelli D, Pons JL, Politti F, Lucareli PRG. Muscle synergies analysis shows altered neural strategies in women with patellofemoral pain during walking. PLOS ONE. 2023; 18: e0292464.
[32] Fan P, Yang Z, Wang T, Li J, Kim Y, Kim S. Neuromuscular control strategies in basketball shooting: distance-dependent analysis of muscle synergies. Journal of Sports Science and Medicine. 2024; 23: 571–580.
[33] Santuz A, Ekizos A, Janshen L, Baltzopoulos V, Arampatzis A. On the methodological implications of extracting muscle synergies from human locomotion. International Journal of Neural Systems. 2017; 27: 1750007.
[34] Li M, Dong M, Wang T, Lu Y, Bum CH, Kim S. Effects of static stretching and its combination with conditioning contractions on lower limb muscle synergy and squat jump performance at two initial knee joint angles. Journal of Men's Health. 2024; 20: 101–110.
[35] Lee DD, Seung HS. Learning the parts of objects by non-negative matrix factorization. Nature. 1999; 401: 788–791.
[36] Kerkman JN, Bekius A, Boonstra TW, Daffertshofer A, Dominici N. Muscle synergies and coherence networks reflect different modes of coordination during walking. Frontiers in Physiology. 2020; 11: 751.
[37] Alexander RM. A minimum energy cost hypothesis for human arm trajectories. Behavioral and Brain Sciences. 1997; 76: 97–105.
[38] Lephart SM, Henry TJ. The physiological basis for open and closed kinetic chain rehabilitation for the upper extremity. Journal of Sport Rehabilitation. 1996; 5: 71–87.
[39] Lear LJ, Gross MT. An electromyographical analysis of the scapular stabilizing synergists during a push-up progression. Journal of Orthopaedic & Sports Physical Therapy. 1998; 28: 146–157.
[40] Lee JH, Park JS, Jeong WK. Importance of initial peak torque of the supraspinatus muscle during shoulder flexion. Clinics in Orthopedic Surgery. 2022; 14: 272–280.
[41] Mansfield PJ, Neumann DA. Essentials of kinesiology for the physical therapist assistant. 3rd edn. Mosby: St. Louis. 2018.
[42] Ludewig PM, Hoff MS, Osowski EE, Meschke SA, Rundquist PJ. Relative balance of serratus anterior and upper trapezius muscle activity during push-up exercises. The American Journal of Sports Medicine. 2004; 32: 484–493.
[43] Collins KS, Bradley AP, Christensen BK, Waldera RW, Klawitter LA, Ogren L, *et al*. Bench press range-of-motion and velocity-based repetition control: effects on ballistic push-up performance in males. International Journal of Exercise Science. 2024; 17: 38–53.
[44] Bagg SD, Forrest WJ. A biomechanical analysis of scapular rotation during arm abduction in the scapular plane. American Journal of Physical Medicine & Rehabilitation. 1988; 67: 238–245.
[45] Hasan S, Iqbal A, Alghadir AH, Alonazi A, Alyahya D. The combined effect of the trapezius muscle strengthening and pectoralis minor muscle stretching on correcting the rounded shoulder posture and shoulder flexion range of motion among young Saudi females: a randomized comparative study. Healthcare. 2023; 11: 500.
[46] Myers JB, Oyama S, Wassinger CA, Ricci RD, Abt JP, Conley KM, *et al*. Reliability, precision, accuracy, and validity of posterior shoulder tightness assessment in overhead athletes. The American Journal of Sports Medicine. 2007; 35: 1922–1930.
[47] Marcolin G, Petrone N, Moro T, Battaglia G, Bianco A, Paoli A. Selective activation of shoulder, trunk, and arm muscles: a comparative analysis of different push-up variants. Journal of Athletic Training. 2015; 50: 1126–1132.
[48] Kristiansen M, Samani A, Vuillerme N, Madeleine P, Hansen EA. External and internal focus of attention increases muscular activation during bench press in resistance-trained participants. Journal of Strength and Conditioning Research. 2018; 32: 2442–2451.
[49] Grgic J, Mikulic I, Mikulic PJS. Acute and long-term effects of attentional focus strategies on muscular strength: a meta-analysis. Sports. 2021; 9: 153.
[50] Steele KM, Tresch MC, Perreault EJ. The number and choice of muscles impact the results of muscle synergy analyses. Frontiers in Computational Neuroscience. 2013; 7: 105.
[51] Garcia-Retortillo S, Romero-Gómez C, Ivanov PC. Network of muscle fibers activation facilitates inter-muscular coordination, adapts to fatigue and reflects muscle function. Communications Biology. 2023; 6: 891.

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