

Research article

## Effects of Attachment Type on Phase-Specific Surface Electromyographic Amplitude During The Front Lat Pulldown: A Randomized Crossover Study

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### Abstract

This randomized crossover study compared surface electromyographic (sEMG) amplitude across cadence-defined lifting and lowering analytical intervals under four front lat pulldown attachment conditions in resistance-trained men. Sixteen participants performed the exercise with a straight bar, wide V-shaped handle, cambered bar, and rope. Each condition was performed at 70% of its attachment-specific 1-repetition maximum using a metronome-prescribed nominal 2-second lifting and 2-second lowering cadence and standardized grip-width criteria. sEMG was recorded from the latissimus dorsi, middle trapezius, posterior deltoid, biceps brachii, and triceps brachii. Normalized root mean square amplitudes were analyzed with repetition-level linear mixed-effects models, and sensitivity analyses were used to examine robustness. The most consistent attachment-related findings were greater biceps brachii sEMG amplitude in the wide V-shaped handle condition, particularly in the lifting analytical interval, and greater posterior deltoid sEMG amplitude in the rope than cambered-bar condition. Middle trapezius sEMG amplitude was greater in the cadence-defined lowering analytical interval than in the lifting interval. Specifically, the rope exceeded the cambered bar for posterior deltoid sEMG amplitude (mean difference = 8.0 %MVIC, 95% CI = 4.1 to 11.9;  $p = 0.002$ ), and the wide V-shaped handle showed greater biceps brachii sEMG amplitude in the lifting analytical interval than the straight bar, cambered bar, and rope (mean differences = 11.0 to 15.7 %MVIC; all  $p < 0.001$ ). Middle trapezius sEMG amplitude was greater in the lowering analytical interval than in the lifting analytical interval (mean difference = 6.2 %MVIC, 95% CI = 3.3 to 9.1;  $p < 0.001$ ). No consistent between-condition difference was found for latissimus dorsi sEMG amplitude; a small attachment-by-phase interaction in the primary model was attenuated in complete-case sensitivity analysis. Because relative intensity was standardized to attachment-specific 1RM, absolute loads differed among conditions. The results therefore describe differences among attachment-specific relative-load conditions and should not be attributed solely to attachment geometry. The lifting and lowering labels refer to cadence-defined analytical intervals rather than mechanically synchronized phase boundaries, and acute sEMG findings should not be interpreted as evidence of longer-term hypertrophy or strength adaptations.

**Key words:** Surface electromyography, resistance exercise, exercise technique, sEMG amplitude, strength training.

### Introduction

Upper-body pulling exercises are widely used in strength and conditioning programs to develop pulling capacity, add accessory training volume, and complement pressing-

dominant training (American College of Sports Medicine, 2009; Fleck and Kraemer, 2014). In day-to-day coaching, the cable attachment or handle used for the front lat pulldown is often selected to emphasize the back, arms, or posterior shoulder. Because resistance-training adaptations are task specific and influenced by exercise selection and range of motion, common variations of an exercise should not be assumed to impose identical local demands (Baz-Valle et al., 2019; Pallares et al., 2021). For practitioners, the key question is whether changing the attachment can meaningfully shift the pattern of local sEMG amplitude across the back, shoulder, and arm muscles without changing the broader exercise category.

The front lat pulldown is a common machine-based pulling exercise because it is technically accessible and compatible with several commercially available attachments (Graham, 2003; Snarr et al., 2015). The movement combines shoulder adduction and/or shoulder extension with elbow flexion and elicits measurable sEMG amplitude in the latissimus dorsi and several synergist muscles (Lehman et al., 2004). Previous studies have examined grip width, forearm orientation, front-versus-back execution, and hand position during lat pulldown variations (Andersen et al., 2014; Lusk et al., 2010; Padovan et al., 2024; Signorile et al., 2002; Sperandei et al., 2009). However, many studies have summarized sEMG amplitude across the whole repetition. Whole-repetition averages may obscure whether a between-condition difference occurs mainly during the lifting or controlled lowering portion of the repetition.

Attachment geometry may affect wrist alignment, distal freedom, and force transmission from the hands to the external load. This is not a trivial equipment detail, because handles are often selected in practice with the expectation that they will target specific muscles. If that expectation is valid, different attachments should not merely change comfort or grip feel; they should produce identifiable shifts in the monitored muscle and portion of the repetition in which local sEMG amplitude is increased. Surface electromyography should still be interpreted within appropriate limits because it reflects electrical signals recorded at the electrode site and does not directly quantify whole-muscle force, muscle contribution, hypertrophy potential, or long-term training superiority (Merletti et al., 2001; Vieira and Botter, 2021; Vigotsky et al., 2018).

The practical issue is therefore not whether one attachment produces the highest global sEMG amplitude, but whether attachment configuration alters the pattern of

local sEMG amplitude across operationally defined portions of a commonly used pulling exercise. Clarifying this issue may help coaches and practitioners select front lat pulldown variations according to the desired local emphasis while avoiding unsupported assumptions about selective latissimus dorsi targeting. This interval-specific approach extends previous whole-repetition comparisons by identifying whether attachment effects reflect a general increase in sEMG amplitude or a redistribution of sEMG amplitude among synergistic muscles across the cadence-defined lifting and lowering analytical intervals. Therefore, this randomized crossover study compared normalized sEMG amplitude of the latissimus dorsi, middle trapezius, posterior deltoid, biceps brachii, and triceps brachii across four common attachments and the cadence-defined lifting and lowering analytical intervals of the front lat pulldown. Based on the different hand constraints and distal freedom created by the attachments, we hypothesized that the wide V-shaped handle would increase elbow-flexor sEMG amplitude, the rope would increase posterior-shoulder sEMG amplitude, and attachment-related differences would be more evident in the lifting analytical interval than in the lowering analytical interval. We did not expect any single attachment to uniformly increase latissimus dorsi sEMG amplitude across intervals.

## Methods

### Participants

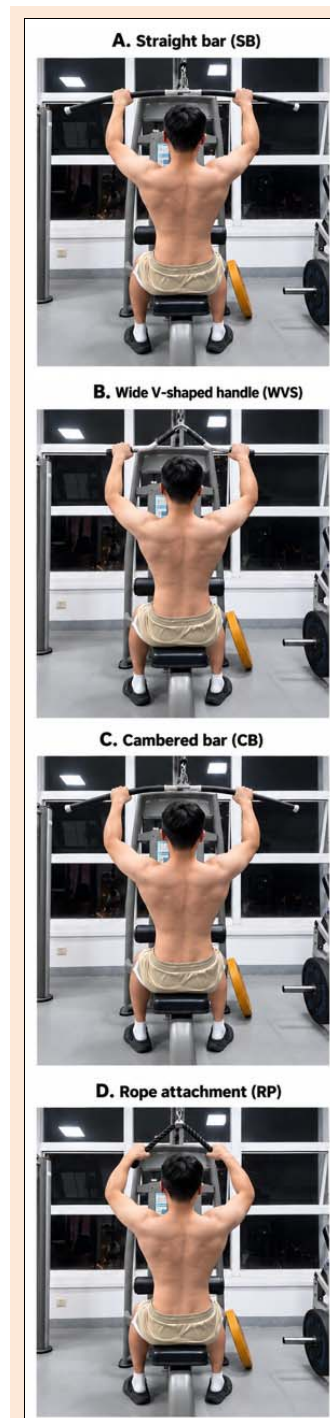
An a priori sample-size calculation based on previous between-condition differences in lat pulldown sEMG amplitude indicated that at least 14 participants were required ( $\alpha = 0.05$ , power = 0.80, Cohen's  $f = 0.35$ ) (Signorile et al., 2002). The calculation was performed using G\*Power for a repeated-measures within-participant design and treated the primary comparison as an effect across attachment conditions. Sixteen resistance-trained men were recruited (Table 1) to account for possible signal loss or unusable repetitions. After data-quality processing, 13 to 14 participants contributed to the muscle-specific models. Eligibility criteria were at least 3 years of resistance-training experience, training at least twice weekly, and no upper-extremity, shoulder, or spinal musculoskeletal injury within the previous 6 months. Participants avoided strenuous upper-body exercise, alcohol, caffeine, and other stimulants for 24 hours before testing, and additional resistance training was avoided during the experimental period.

**Table 1.** Participant characteristics and attachment-specific one-repetition maximum values.

| Variable                      | Enrolled sample<br>(n = 16) |
|-------------------------------|-----------------------------|
| Age (years)                   | 20.1 ± 0.9                  |
| Body height (m)               | 1.79 ± 0.05                 |
| Body mass (kg)                | 70.6 ± 5.1                  |
| Straight bar 1RM (kg)         | 76.4 ± 5.7                  |
| Wide V-shaped handle 1RM (kg) | 69.4 ± 3.6                  |
| Cambered bar 1RM (kg)         | 74.4 ± 5.8                  |
| Rope 1RM (kg)                 | 64.4 ± 7.1                  |

Values are mean ± SD. 1RM = one-repetition maximum. Sixteen resistance-trained men were enrolled. Fourteen participants contributed to the primary analyses, and 13 - 14 participants contributed to the muscle-specific models after surface electromyography (sEMG) data-quality processing.

The study was approved by the local institutional ethics committee (approval no. 2025LCLL-120) and prospectively registered in the Chinese Clinical Trial Registry (ChiCTR2500110939). All procedures were performed in accordance with the Declaration of Helsinki, and all participants provided written informed consent before participation. Written informed consent for publication of identifiable photographs was also obtained from the participant/model shown in Figure 2 and Supplementary Figure S1.



**Figure 2.** Standardized starting positions for the four front lat pulldown attachment conditions. Photographs show the actual experimental equipment, participant positioning, and attachment configurations. SB = straight bar; WVS = wide V-shaped handle; CB = cambered bar; RP = rope attachment.

### Experimental approach to the problem

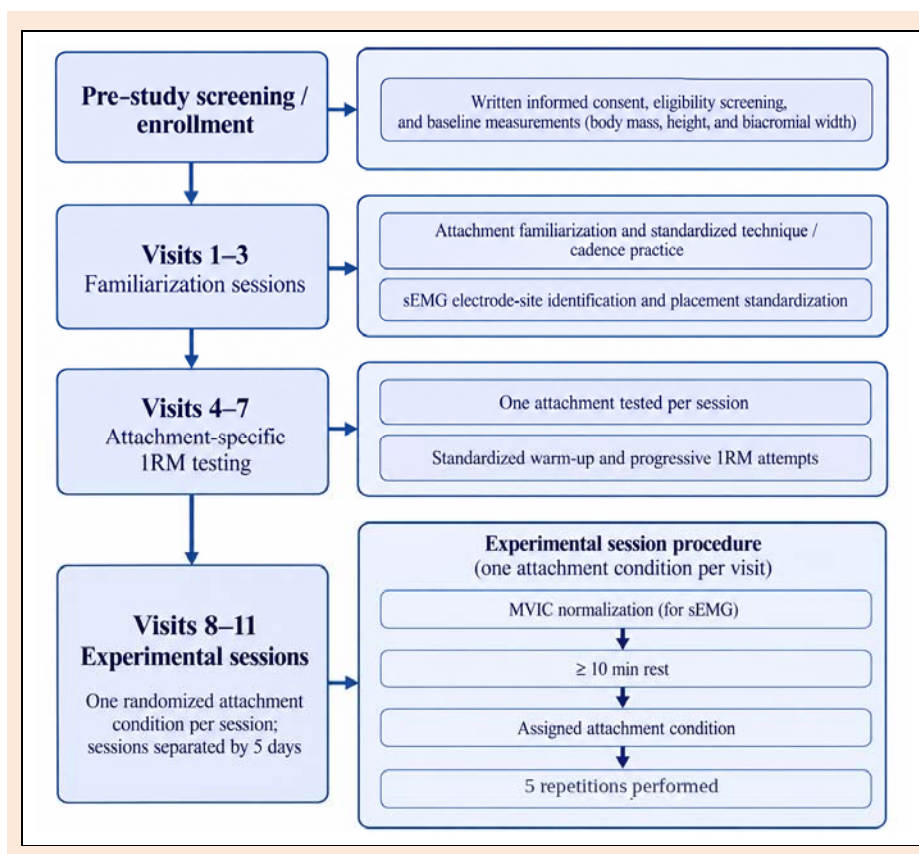
A randomized crossover design was used to compare normalized sEMG amplitude across attachment conditions and cadence-defined lifting and lowering analytical intervals during the front lat pulldown. Participants completed the exercise with four attachments: straight bar, wide V-shaped handle, cambered bar, and rope. Condition order for the experimental sessions was randomized using a Williams balanced Latin-square scheme. Grip width was standardized to 1.5 times biacromial width, consistent with previous grip-width work in the lat pulldown (Lusk et al., 2010). The practical reference for grip width was the distance between standardized hand contact points on each attachment. For the straight bar and cambered bar, this was measured between the centers of the index-finger contact points; for the wide V-shaped handle, it was measured between the centers of the handle contact points; and for the rope, both hands were placed symmetrically at marked rope positions to maintain the closest possible effective grip width. The rope condition used a pronated pulling strategy. Experimental loads were prescribed as 70% of attachment-specific one-repetition maximum (1RM) to standardize relative intensity. This choice necessarily produced different absolute loads when attachment-specific 1RM values differed. Participants attended 11 laboratory sessions: three familiarization sessions, four attachment-specific 1RM testing sessions, and four experimental sessions. The four experimental sessions were separated by five days. Flowchart of the randomized crossover laboratory visit sequence was given at Figure 1.

### Procedures

#### Familiarization

During the three familiarization sessions, participants completed anthropometric assessment, practiced the front lat pulldown with each attachment, and became familiar with the standardized cadence and technique criteria. Electrode sites were also identified and checked to improve placement consistency across later sessions. Attachment configurations are shown in Figure 2.

Each repetition began from a seated start position with a pronated grip, full elbow extension with the arms extended overhead, the thighs fixed beneath the leg pad, and the pelvis stabilized on the seat. Participants maintained a slight torso recline throughout the repetition to avoid bar-head contact while minimizing trunk motion. The attachment was pulled in front of the body toward the upper- to mid-chest during the intended lifting portion, with the elbows drawn downward without excessive backward displacement, and returned under control to the starting position during the intended lowering portion. A metronome prescribed a nominal 2-second lifting and 2-second lowering cadence. Acceptable technique required full elbow extension at the start and end of the repetition, an upper- to mid-chest endpoint, symmetrical hand placement, stable pelvis and thigh contact with the pad, and no progressive trunk layback. A repetition was repeated or excluded when the participant clearly failed to follow the prescribed metronome rhythm, failed to reach the standardized endpoint, failed to return to full elbow extension, showed visible hand asymmetry or grip slippage, or



**Figure 1.** Flowchart of the randomized crossover laboratory visit sequence.

showed excessive trunk movement. Technique and cadence compliance were screened during testing and later reviewed offline from the movement trajectory; sEMG recordings were reviewed separately for signal quality. The standardized front lat pulldown technique required during testing is illustrated in Supplementary Figure S1.

### Attachment-specific 1RM testing

One-repetition maximum (1RM) testing was performed separately for the straight bar, wide V-shaped handle, cambered bar, and rope. For each condition, participants completed a standardized warm-up followed by progressively heavier single-repetition attempts. Load was increased until the participant could no longer complete the repetition through the standardized range of motion without technique deviation. Three to five minutes of rest were provided between maximal attempts, and the heaviest successfully completed load was recorded as the condition-specific 1RM. Each attachment-specific 1RM was assessed in its own laboratory session. At least 48 hours separated each 1RM session from the corresponding experimental session.

### Experimental sessions

At each experimental session, participants first performed maximal voluntary isometric contraction (MVIC) testing for the monitored muscles. The MVICs were used to provide the normalization reference for the sEMG data. Three 5-second trials were completed per muscle with 3 minutes of rest between trials, and muscle order was randomized across participants to reduce order and fatigue effects (Konrad, 2005). The same assessor provided manual resistance and standardized verbal encouragement across trials, and posture was standardized within participants. For the latissimus dorsi, participants were seated with the upper arm alongside the trunk and the elbow flexed to 90 degrees; they performed maximal isometric humeral extension against manual resistance while depressing the shoulder girdle. For the middle trapezius, participants were seated and performed maximal scapular retraction against a fixed resistance. For the posterior deltoid, the upper arm was abducted to 90 degrees, resistance was applied near the elbow, and participants performed maximal isometric humeral extension. For the biceps brachii, participants maintained the upper arm close to the trunk with the elbow at approximately 90 degrees and performed maximal isometric elbow flexion against manual resistance. For the triceps brachii, participants stood with the upper arm alongside the trunk and the elbow flexed to approximately 45 degrees and performed maximal isometric elbow extension against resistance. Manual stabilization was applied as needed to limit compensatory movement. After at least 10 minutes of rest, participants performed the front lat pulldown with the attachment assigned to that experimental session.

Participants performed five repetitions at 70% of attachment-specific 1RM during each experimental session. Repetitions were first screened for technique, cadence compliance, and sEMG signal quality, with emphasis placed on technically consistent early-set observations. When an earlier repetition was unusable because of technique or cadence deviation, electrode detachment, abnormal signal noise, or marked movement artifact, the next eligible repetition was used. The retained valid repetitions

from this screening were used to define the participant-specific right-latissimus-dorsi activity-onset reference described below. After EMG-defined activity onset had been determined, analytical-window availability was assessed; an observation was excluded at the segmentation stage if sufficient signal duration was not available for the predefined analytical windows. Exclusion decisions were made during data collection when clear deviations were visible and were confirmed during offline signal-quality and analytical-window checks. Because attachment type was visually apparent, assessors were not blinded to attachment condition during technique screening. Only observations passing the signal-quality and analytical-window availability checks entered the statistical models. The retained-repetition distribution is reported in Supplementary Table S3.

### Surface electromyography and analytical-interval definition

Surface electromyography (sEMG) was recorded from the right latissimus dorsi, middle trapezius, posterior deltoid, biceps brachii, and triceps brachii using wireless bipolar bar electrodes (Trigno Avanti, Delsys, USA; interelectrode distance 10 mm). Signals were acquired using EMGworks Acquisition v4.8.0 (Delsys, USA). Right-side recording was selected to standardize setup time and electrode placement across conditions; it was not intended to assume bilateral equivalence. Hand dominance was not used as an eligibility criterion or entered into the analysis; therefore, potential dominance-related or side-to-side differences could not be evaluated. Electrode placement used Barbero et al., (2012) as the primary anatomical reference, with Zipp (1982) and SENIAM-related recommendations used to support standardized surface-electrode orientation and reporting (Hermens et al., 2000; Zipp, 1982). The CEDE electrode-selection matrix was used as a reporting and methodological standardization reference rather than as an anatomical placement atlas (Besomi et al., 2019).

Skin was prepared by shaving when necessary, gentle abrasion, and cleaning with alcohol before electrode placement. For the latissimus dorsi, electrodes were placed over the muscle belly inferior to the scapula and lateral to the thoracolumbar region, aligned with the local fiber direction. For the middle trapezius, electrodes were placed over the muscle belly between the medial scapular border and thoracic spinous processes; because local middle-trapezius fibers run primarily mediolaterally in the selected region, the electrode bars were oriented transversely relative to the spine and parallel to the local fiber direction. For the posterior deltoid, electrodes were placed over the posterior shoulder muscle belly inferior to the posterior acromion and aligned toward the deltoid tuberosity. For the biceps brachii, electrodes were placed over the anterior upper-arm muscle belly and aligned with the longitudinal fiber direction. For the triceps brachii, electrodes were placed over the posterior upper-arm muscle belly and aligned with the longitudinal fiber direction. The same assessor located electrode sites across sessions using anatomical landmarks; exact between-session replication cannot be guaranteed because electrodes were removed after each session. Signals were sampled at 2048 Hz.

Raw sEMG signals were band-pass filtered (20 - 400 Hz), full-wave rectified, and converted to root mean

square (RMS) amplitude (Konrad, 2005; Merletti et al., 2001). RMS amplitude was calculated separately for the cadence-defined lifting and lowering analytical intervals of each valid repetition, normalized to the peak 1-second MVIC value of the corresponding muscle, and expressed as percentage of MVIC (%MVIC). The highest 1-second RMS window across the three MVIC trials was used as the normalization reference for each muscle, consistent with common sEMG normalization approaches using maximal voluntary contractions as the reference condition (Burden, 2010; Halaki and Ginn, 2012).

Three-dimensional kinematic data were collected using a Qualisys motion-capture system (Qualisys AB, Gothenburg, Sweden) consisting of 10 Arqus cameras and one synchronization unit, at a sampling frequency of 200 Hz. Ground reaction force data were collected using Bertec three-dimensional force plates (Bertec Corporation, Columbus, OH, USA) at 1000 Hz. Before each experimental session, the capture volume was calibrated according to the manufacturer's procedures, and marker trajectories were checked during acquisition and offline processing to ensure adequate reconstruction quality.

Reflective markers were placed according to the upper-body component of the official H-Motion full-body marker model. This marker set included anatomical landmarks required to reconstruct the trunk, shoulder girdle, upper arm, forearm, and hand segments. In the present analysis, the motion-capture data were used to independently characterize movement execution, including range of motion, cadence, endpoint criteria, and velocity-defined active-motion duration. Because the motion-capture and sEMG systems did not share a common time base, kinematic events were not used to assign individual sEMG samples to mechanical phases.

Raw kinematic and kinetic data were processed in Visual3D x64 Professional v2023.06.7 (C-Motion, Inc., Germantown, MD, USA). Marker trajectories and model-derived variables used for kinematic verification were low-pass filtered using the Visual3D low-pass filtering function with a cut-off frequency of 15 Hz. A velocity-based kinematic event algorithm applied to the reconstructed upper-body marker trajectories was used to derive pull and return active-motion durations. These values represent the velocity-defined active-motion portions associated with movement toward and away from the chest; they are distinct from, and were not intended to reproduce, the complete nominal 2.0-second metronome-prescribed lifting or lowering intervals. Participant-by-attachment mean active-motion durations were used for independent cadence characterization and as covariates in the duration-adjusted sensitivity analysis. They were not used to time-register the sEMG record or to assign mechanical events to individual sEMG samples.

Before each trial, the motion-capture system was started first, followed by the sEMG system. Once both systems were recording, a standardized verbal command was given for the participant to begin the front lat pulldown. For sEMG analytical-window definition, repetition-activity onset was operationally identified from the right latissimus dorsi (LD) sEMG channel. After the 20 - 400 Hz band-pass filtering and full-wave rectification described above, the

processed right-LD signal was represented as a 50-ms moving RMS envelope. For each participant, a reference amplitude was defined as the highest right-LD RMS value observed across all retained valid repetitions and all four attachment conditions. The activity-onset threshold was set at 20% of this participant-specific cross-condition maximum RMS amplitude and therefore remained fixed within each participant across attachment conditions and repetitions. EMG-defined activity onset was assigned to the first sample at which the right-LD RMS envelope exceeded this threshold and remained continuously above it for at least 50 ms. This EMG-defined repetition-activity onset was used solely as a reproducible analytical temporal anchor and was not interpreted as the mechanical onset of the repetition. The subsequent nominal 2-second lifting and 2-second lowering intervals prescribed by the metronome were used to define broad cadence-defined analytical windows for sEMG quantification rather than mechanically synchronized phase boundaries. For readability, these windows are referred to as the lifting and lowering analytical intervals; the labels describe the intended portions of the repetition and do not denote precisely identified mechanical phases. Because no common hardware trigger, common clock, or shared timestamp was used, precise frame-by-frame or sample-by-sample temporal correspondence between the kinematic and sEMG signals could not be established. The independently recorded motion-capture data were used to characterize movement execution and active-motion duration, not to establish event-level synchronization with individual sEMG samples.

### Statistical analysis

All analyses were performed in R 4.4.1 within RStudio. Primary inference used the available analytical-interval observations remaining after segmentation and data-quality processing. Descriptive values were averaged within each participant, muscle, attachment, and analytical-interval cell, whereas inferential models used repetition-level observations. This modelling approach was used to retain valid repeated observations while accounting for within-participant clustering through random effects rather than treating repetitions as independent participants.

Linear mixed-effects models were fitted separately for each muscle. Attachment, phase (operationally representing the cadence-defined lifting versus lowering analytical interval), and their interaction were included as fixed effects. The final primary model for each muscle included a participant-level random intercept and followed the form  $\text{sEMG amplitude} \sim \text{attachment} \times \text{phase} + (1 \mid \text{participant})$ . More complex participant-level random-effects structures were considered during model checking but were simplified after singular-fit diagnostics; the final structures are reported in Supplementary Table S4. Type III tests with Satterthwaite approximation were used for inference. Bonferroni-adjusted pairwise comparisons were used for significant main effects and simple effects. Statistical significance was set at  $p < 0.05$ . Model-based estimates and 95% confidence intervals were used to support interpretation alongside  $p$  values.

Two sensitivity analyses were reported in the supplementary material: models restricted to observations

from original repetition positions 1 and 2 and models restricted to participants with complete observations for all four attachment-by-two analytical-interval combinations. The supplementary material also reports retained analytical-interval observations, the distribution of original repetition positions, interquartile-range-based outlier-screening diagnostics, and the final random-effects structure used for the primary models (Supplementary Tables S1, S2, S3 and S4). These diagnostic summaries were used for transparency and were not applied as automatic exclusion criteria. To address the different absolute loads produced by attachment-specific 1RM values, the primary attachment-by-phase model was also refitted with actual experimental load as a covariate, with an additional load-by-phase model used as a robustness check; these analyses are reported in Supplementary Table S9 and were not interpreted as isolating a pure attachment-geometry effect.

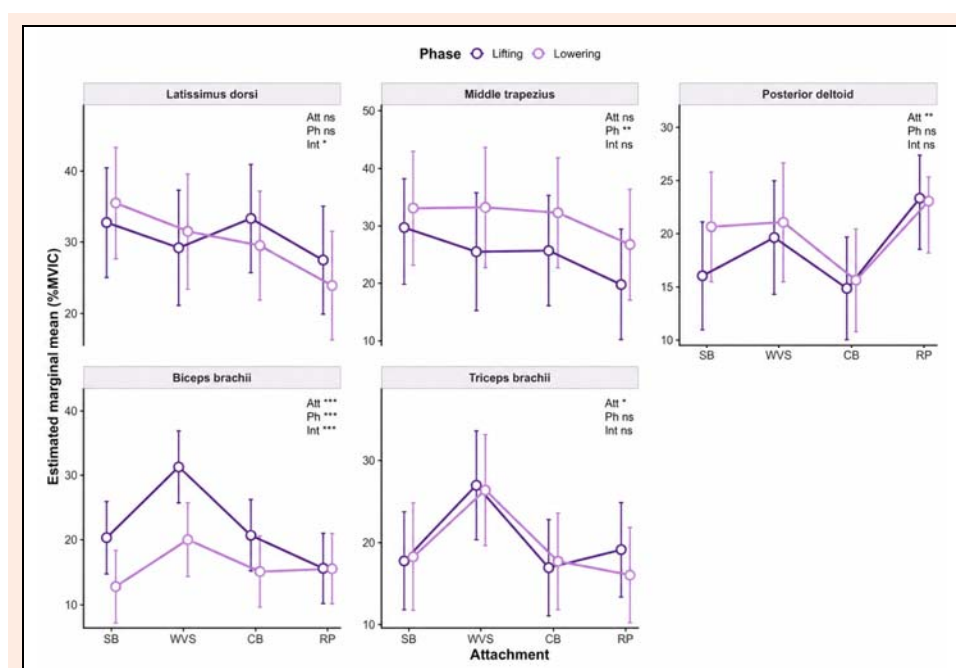
Temporal robustness was evaluated using complementary sensitivity analyses that addressed different aspects of uncertainty created by the absence of hardware synchronization. First, velocity-defined pull and return active-motion durations were quantified independently from motion capture (Supplementary Table S5), and the principal sEMG contrasts were re-estimated with participant-by-attachment mean active-motion duration entered as the corresponding interval-specific covariate (Supplementary Table S6). Second, 1-second analytical windows were systematically shifted by -500, -250, 0, +250, and +500 ms relative to the EMG-defined activity onset to test sensitivity to substantial temporal displacement (Supplementary Table S7). The 0-ms condition represents the reference placement of the 1-second sensitivity window rather than the primary full 2-second analytical interval; its numerical estimates therefore are not expected to reproduce the primary-model estimates. Third, a boundary-free nominal 4.0-second analytical-window analysis used a continuous 4.0-second window beginning at the same 20% EMG-

defined activity onset and omitted the lifting/lowering phase term entirely (Supplementary Table S8). These analyses were designed to test whether the principal findings depended materially on the assumed analytical timing; they do not validate or retrospectively identify the true mechanical lifting-to-lowering boundary. Intermuscular coordination metrics, such as normalized mutual information, were not calculated because the aim was to compare single-muscle sEMG amplitude patterns rather than coordination among muscles.

## Results

### Overview

Fourteen participants contributed to the primary analyses; 13 to 14 participants contributed to the muscle-specific models because of residual missing observations. Missing observations resulted from analytical-window availability, cadence or technique deviations, or signal-quality exclusions rather than participant withdrawal. Retained observations and the distribution of original repetition positions are reported in Supplementary Tables S2 and S3. The inferential pattern differed by muscle: posterior deltoid and triceps brachii showed between-condition differences, middle trapezius showed an analytical-interval effect, biceps brachii showed condition, interval, and condition-by-interval differences, and latissimus dorsi showed a smaller condition-by-interval interaction without clear main effects (Figure 3; Supplementary Table S1). Figure 3 presents the model-based estimates and 95% confidence intervals, and Supplementary Figure S2 shows the raw observations. Participant-level descriptive mean  $\pm$  SD values for each muscle  $\times$  attachment  $\times$  analytical-interval combination are provided in Supplementary Table S10. For readability in the Results, the terms lifting and lowering refer to the cadence-defined analytical intervals and should not be interpreted as mechanically synchronized movement phases.



**Figure 3.** Estimated marginal means of sEMG amplitude across attachment conditions and cadence-defined analytical intervals.

### Between-condition differences

Between-condition differences were clearest for the posterior deltoid, biceps brachii, and triceps brachii. For the posterior deltoid, there was a condition effect ( $p = 0.003$ ), whereas the phase main effect and condition-by-phase interaction were not significant. Bonferroni-adjusted comparisons showed greater posterior deltoid sEMG amplitude in the rope condition than in the cambered-bar condition (mean difference = 8.0 %MVIC, 95% CI = 4.1 to 11.9;  $p = 0.002$ ). For the biceps brachii, condition, phase, and condition-by-phase effects were significant (all  $p < 0.001$ ). In the lifting analytical interval, the wide V-shaped handle condition showed greater biceps brachii sEMG amplitude than the straight bar (mean difference = 11.0 %MVIC, 95% CI = 6.5 to 15.6;  $p < 0.001$ ), cambered bar (10.5 %MVIC, 95% CI = 6.0 to 15.0;  $p < 0.001$ ), and rope (15.7 %MVIC, 95% CI = 11.3 to 20.0;  $p < 0.001$ ). In the lowering analytical interval, the only significant condition contrast for the biceps brachii was greater sEMG amplitude with the wide V-shaped handle than with the straight bar (7.1 %MVIC, 95% CI = 2.5 to 11.7;  $p = 0.020$ ). These comparisons describe the complete attachment-specific relative-load conditions; they do not isolate attachment geometry from absolute load.

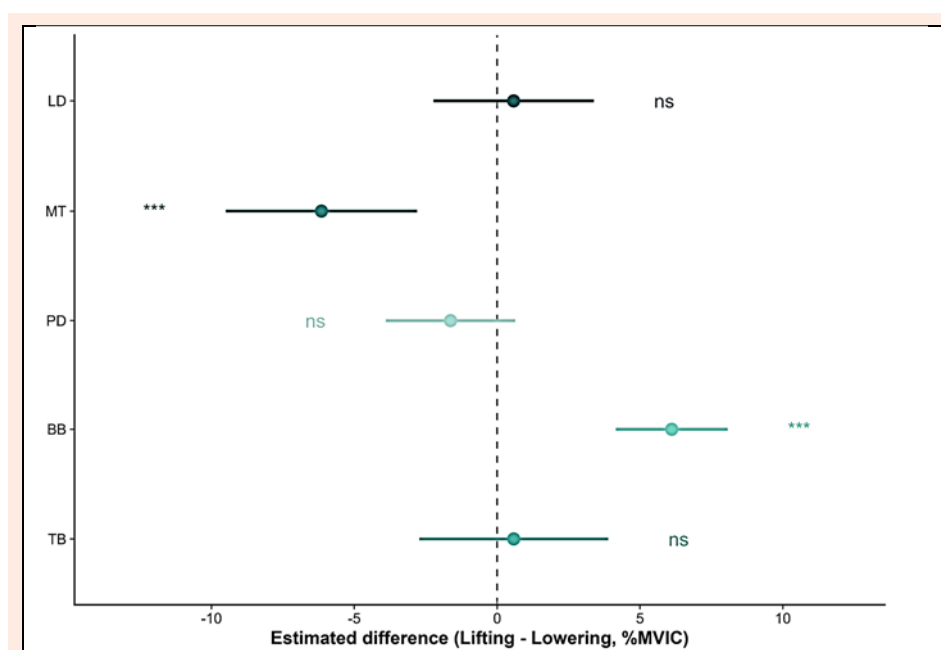
For the triceps brachii, there was a condition effect in the primary model ( $p = 0.025$ ), whereas the phase main effect and interaction were not significant. The wide V-shaped handle condition showed greater triceps brachii sEMG amplitude than the cambered-bar condition (mean difference = 11.3 %MVIC, 95% CI = 3.4 to 19.2;  $p = 0.038$ ) and rope condition (10.8 %MVIC, 95% CI = 3.1 to 18.6;  $p = 0.045$ ). Because the triceps brachii pattern changed in the complete-case sensitivity analysis, these contrasts should be treated as less stable than the posterior deltoid, biceps brachii, and middle trapezius findings. For the latissimus dorsi, neither the condition nor phase main effect was significant, indicating no consistent between-condition difference in latissimus dorsi sEMG amplitude.

### Analytical-interval effects and condition-by-phase interactions

Analytical-interval effects were most evident for the biceps brachii and middle trapezius. Biceps brachii sEMG amplitude was greater in the lifting analytical interval than in the lowering analytical interval for the straight bar, wide V-shaped handle, and cambered bar conditions, but not for the rope condition. For the middle trapezius, there was an analytical-interval effect, with greater sEMG amplitude in the lowering analytical interval than in the lifting analytical interval (mean difference = 6.2 %MVIC, 95% CI = 3.3 to 9.1;  $p < 0.001$ ). This lowering-interval pattern is shown in Figure 4. The latissimus dorsi condition-by-phase interaction reached statistical significance in the primary model ( $p = 0.046$ ), but this effect was attenuated in the complete-case sensitivity analysis ( $p = 0.075$ ). Therefore, latissimus dorsi-related contrasts should be interpreted as exploratory. As exploratory contrasts from the primary model, latissimus dorsi sEMG amplitude in the lowering analytical interval was greater in the straight-bar condition than in the rope condition (mean difference = 11.9 %MVIC, 95% CI = 4.8 to 19.1;  $p = 0.009$ ), and within-condition comparisons showed greater sEMG amplitude in the lifting analytical interval than in the lowering analytical interval for the cambered bar ( $p = 0.046$ ) and rope ( $p = 0.047$ ).

### Sensitivity analyses

Sensitivity analyses supported different levels of robustness for attachment-related findings and analytical-interval effects. Restricting the analysis to original repetition positions 1 and 2, thereby excluding the few observations in which a later repetition replaced an unusable earlier repetition, preserved the overall inferential pattern. In the complete-case analysis, the posterior deltoid condition effect, the full biceps brachii pattern, and the middle trapezius analytical-interval effect were retained. The latissimus dorsi interaction was attenuated ( $p = 0.075$ ), and the triceps brachii result shifted from a condition main effect in the



**Figure 4.** Cadence-defined analytical-interval differences in normalized sEMG amplitude across muscles.

primary model to an interaction pattern in the complete-case subset ( $p = 0.018$ ). Accordingly, latissimus dorsi and triceps brachii should be interpreted as exploratory or less stable findings. The posterior-deltoid and biceps-brachii attachment-related findings showed the strongest robustness across the complementary analyses. The middle-trapezius lowering-versus-lifting analytical-interval difference was also retained in analyses that preserved the interval distinction, but it cannot be evaluated in the boundary-free analysis after removal of the phase term. Independent kinematic characterization quantified velocity-defined active-motion portions that are distinct from the complete nominal metronome intervals; adjustment using participant-by-attachment mean pull/return active-motion duration produced only trivial changes in the principal posterior-deltoid, biceps-brachii, and middle-trapezius contrasts (Supplementary Tables S5-S6). Across the -500 to +500 ms temporal perturbations, the posterior-deltoid rope-versus-cambered-bar contrast, the biceps-brachii wide-V-shaped-handle-versus-rope lifting contrast, and the middle-trapezius lowering-versus-lifting contrast remained supported, whereas the biceps-brachii wide-V-shaped-handle contrasts versus the straight and cambered bars were attenuated under the +250- and +500-ms shifts (Supplementary Table S7). In the boundary-free nominal 4.0-second analytical-window analysis, the posterior-deltoid rope-versus-cambered-bar and biceps-brachii wide-V-shaped-handle-versus-rope contrasts remained significant; the middle-trapezius analytical-interval contrast was not estimable after removal of the phase term, and the latissimus-dorsi attachment omnibus test was not significant (Supplementary Table S8). Absolute-load adjustment preserved the direction and statistical support of the key contrasts, although the magnitude of some estimates changed; no load-by-phase interaction was significant for any muscle (all  $p \geq 0.095$ ; Supplementary Table S9).

## Discussion

The main finding of this randomized crossover study was that sEMG amplitude differed across the four attachment-specific relative-load conditions and the cadence-defined analytical intervals in a muscle-dependent manner. The most consistent attachment-related findings were greater biceps brachii sEMG amplitude in the wide V-shaped handle condition, particularly in the lifting analytical interval, and greater posterior deltoid sEMG amplitude in the rope than cambered-bar condition. The middle trapezius showed greater sEMG amplitude in the lowering analytical interval than in the lifting analytical interval. In contrast, no consistent between-condition difference was found for the latissimus dorsi. Because each condition used 70% of its own 1RM, these findings reflect the combined experimental condition, including both attachment configuration and the absolute load associated with that attachment-specific relative intensity. They should therefore not be interpreted as the isolated effect of attachment geometry.

The greater posterior deltoid sEMG amplitude in the rope condition suggests that this condition placed a different acute demand on the posterior shoulder than the cambered-bar condition. The mechanism cannot be

assigned to the rope geometry alone because absolute loads also differed among conditions. A plausible contribution is the different distal constraint and coordination demand near the end of the pull. Previous pulling and shoulder-exercise studies support the broader view that exercise configuration can alter posterior-shoulder sEMG amplitude, although those studies differ from the present work in sample characteristics, task constraints, loading, and normalization procedures (Botton et al., 2013; Tanimoto et al., 2025; Urbanczyk et al., 2020).

The biceps brachii showed the most consistent attachment-related analytical-interval difference. The wide V-shaped handle condition produced the greatest biceps brachii sEMG amplitude, primarily in the lifting analytical interval. This finding is relevant to exercise selection because a wide V-shaped handle is often chosen as a back-training variation, yet one of the clearest sEMG patterns in the present study was greater elbow-flexor amplitude in the intended pulling portion of the repetition. Notably, the wide V-shaped handle condition used a lower mean absolute load than the straight-bar and cambered-bar conditions, so a simple explanation that greater load always produced greater sEMG amplitude does not account for this result. Previous lat pulldown and pull-up studies have also shown that elbow-flexor sEMG amplitude can vary with hand position, exercise configuration, and shoulder-loading strategy (Dickie et al., 2017; Handa et al., 2005; Signorile et al., 2002; Urbanczyk et al., 2020).

The absence of a consistent latissimus dorsi difference is important for the practical interpretation of the study. No condition showed a main-effect difference for latissimus dorsi sEMG amplitude, and the condition-by-phase interaction from the primary model weakened in the complete-case sensitivity analysis. These results do not support the common assumption that using a particular pulldown handle necessarily produces different latissimus dorsi sEMG amplitude under attachment-specific relative loading. A more cautious interpretation is that the tested conditions may alter the interval-specific pattern of local latissimus dorsi sEMG amplitude, but these data do not identify a condition that consistently maximizes it. This interpretation is compatible with studies reporting limited latissimus dorsi differentiation across moderate grip-width, hand-position, and front-versus-back pulldown variations (Andersen et al., 2014; Buonsenso et al., 2025; Lehman et al., 2004; Lusk et al., 2010; Padovan et al., 2024; Signorile et al., 2002; Sperandei et al., 2009; Tanimoto et al., 2025), while recognizing that other studies have reported differences with specific grip or execution choices.

Triceps brachii sEMG amplitude was higher with the wide V-shaped handle than with the cambered bar and rope in the primary model. Because this pattern was less stable in the complete-case analysis, it should be interpreted as a secondary finding. The pattern may reflect a stabilizing or coordinative role at the elbow under standardized relative loading. In contrast, middle trapezius sEMG amplitude was greater in the lowering analytical interval than in the lifting analytical interval. This pattern may be compatible with greater scapular-control demand during the intended return portion of the repetition and is broadly consistent with observations from other pulling

and rowing exercises (Handa et al., 2005; Taboada-Iglesias et al., 2024). However, because the kinematic and sEMG systems were not temporally synchronized, the present data cannot attribute this difference precisely to the mechanically defined lowering phase.

From an applied perspective, the four attachment-specific relative-load conditions produced different local sEMG patterns. The wide V-shaped handle condition showed greater elbow-flexor sEMG amplitude in the lifting analytical interval, whereas the rope condition showed greater posterior deltoid sEMG amplitude than the cambered-bar condition. These observations may help practitioners choose among commonly used pulldown setups when relative intensity is prescribed from each attachment's own 1RM. They should not be used to claim that the attachment alone caused the differences.

Several limitations define the scope of these conclusions. The sample was modest and limited to resistance-trained young men, reducing generalizability and limiting confidence in small or unstable effects. The findings describe acute sEMG responses and should not be interpreted as direct evidence of long-term hypertrophy, strength, or sport-performance adaptations (Vigotsky et al., 2018). The four conditions differed not only in attachment configuration but also in absolute load because experimental loads were prescribed as 70% of attachment-specific 1RM. This design standardized relative intensity, but it prevents the observed between-condition differences from being attributed solely to attachment geometry. The direction of the main findings did not simply follow absolute load: for example, the wide V-shaped handle condition used a lower mean load than the straight-bar and cambered-bar conditions but showed greater biceps brachii sEMG amplitude in the lifting analytical interval, and the rope condition used the lowest mean load but showed greater posterior deltoid sEMG amplitude than the cambered-bar condition. These patterns make a simple 'greater load equals greater sEMG' explanation insufficient, but they do not rule out an influence of absolute load. In an absolute-load-adjusted sensitivity analysis, the directions of the principal posterior-deltoid, biceps-brachii, and middle-trapezius contrasts were retained, although the magnitude of some estimates changed, and no load-by-phase interaction was significant (all  $p > 0.095$ ; Supplementary Table S9). Because absolute load is structurally related to attachment-specific 1RM, however, this covariate analysis cannot isolate a pure attachment-geometry effect. The findings therefore apply specifically to attachment-specific relative-load prescription.

The motion-capture and sEMG systems were recorded independently and did not share a hardware trigger, common clock, or common timestamp. Accordingly, the 20% right-LD EMG-defined activity onset should be interpreted as an analytical timing anchor, and the subsequent nominal 2-second lifting and 2-second lowering periods as broad cadence-defined analytical intervals rather than mechanically synchronized movement boundaries. The velocity-defined active-motion durations derived from motion capture represent active portions of the movement and are distinct from the complete nominal metronome intervals; participant-by-attachment mean durations were used only

as covariates in the duration-adjusted sensitivity analysis and were not time-registered to individual sEMG samples. Electromechanical delay and temporal differences between electrical activation and observable movement mean that samples close to the assumed transition may be misclassified with respect to the true mechanical reversal. The duration-adjusted models, temporal-window perturbation analysis, and boundary-free nominal 4.0-second analytical-window analysis provided complementary checks of timing sensitivity. These analyses supported the strongest attachment-related posterior-deltoid and biceps-brachii findings across complementary timing assumptions, although some biceps-brachii contrasts were attenuated when the analytical windows were shifted later. The middle-trapezius lowering-versus-lifting analytical-interval difference was retained in analyses that preserved the interval distinction but cannot be evaluated in the boundary-free analysis after removal of the phase term. Therefore, these sensitivity analyses do not validate the true mechanical boundary; rather, they indicate that the principal attachment-related conclusions are not wholly dependent on one millisecond-precise nominal transition. For the same reason, more temporally specific analyses, such as the final 0.5 seconds of the intended pulling portion, were not performed because they would have required more precise event-level temporal alignment than was available.

Surface electromyography represents electrical signals recorded at standardized recording sites, not whole-muscle force. This limitation is especially relevant for broad muscles such as the latissimus dorsi and trapezius, where regional heterogeneity, muscle thickness under the electrodes, subcutaneous tissue, crosstalk, electrode orientation, and electrode location relative to innervation zones can influence absolute amplitude values (Barbero et al., 2012; Merletti et al., 2001; Vieira and Botter, 2021; Vigotsky et al., 2018; Zipp, 1982). Because recordings were taken only from the right side, potential bilateral differences in sEMG amplitude could not be evaluated.

## Conclusion

In resistance-trained men, sEMG amplitude differed across front lat pulldown conditions performed at 70% of attachment-specific 1RM and across cadence-defined lifting and lowering analytical intervals. The wide V-shaped handle condition showed the clearest biceps brachii difference, the rope condition showed greater posterior deltoid sEMG amplitude than the cambered-bar condition, and the middle trapezius showed greater sEMG amplitude in the lowering analytical interval than in the lifting analytical interval. No consistent between-condition difference was found for latissimus dorsi sEMG amplitude, and latissimus dorsi- and triceps brachii-related secondary findings were less stable across sensitivity analyses. Because the motion-capture and sEMG systems were not hardware synchronized, the lifting/lowering interval findings should not be interpreted as mechanically validated phase boundaries. Because absolute loads differed among the attachment-specific relative-load conditions, these results should not be attributed solely to attachment geometry. They also should not be interpreted as evidence of superior long-term strength or

hypertrophic adaptations.

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### Key points

- At 70% of attachment-specific 1RM, the wide V-shaped handle elicited greater biceps brachii sEMG amplitude than the other three attachments during the cadence-defined lifting interval.
- The rope attachment elicited greater posterior deltoid sEMG amplitude than the cambered bar, with this finding supported by sensitivity analyses.
- Middle trapezius sEMG amplitude was greater during the cadence-defined lowering analytical interval than during the lifting interval.
- No consistent between-attachment differences were observed in latissimus dorsi sEMG amplitude, suggesting that no single attachment consistently maximized its recorded activity.

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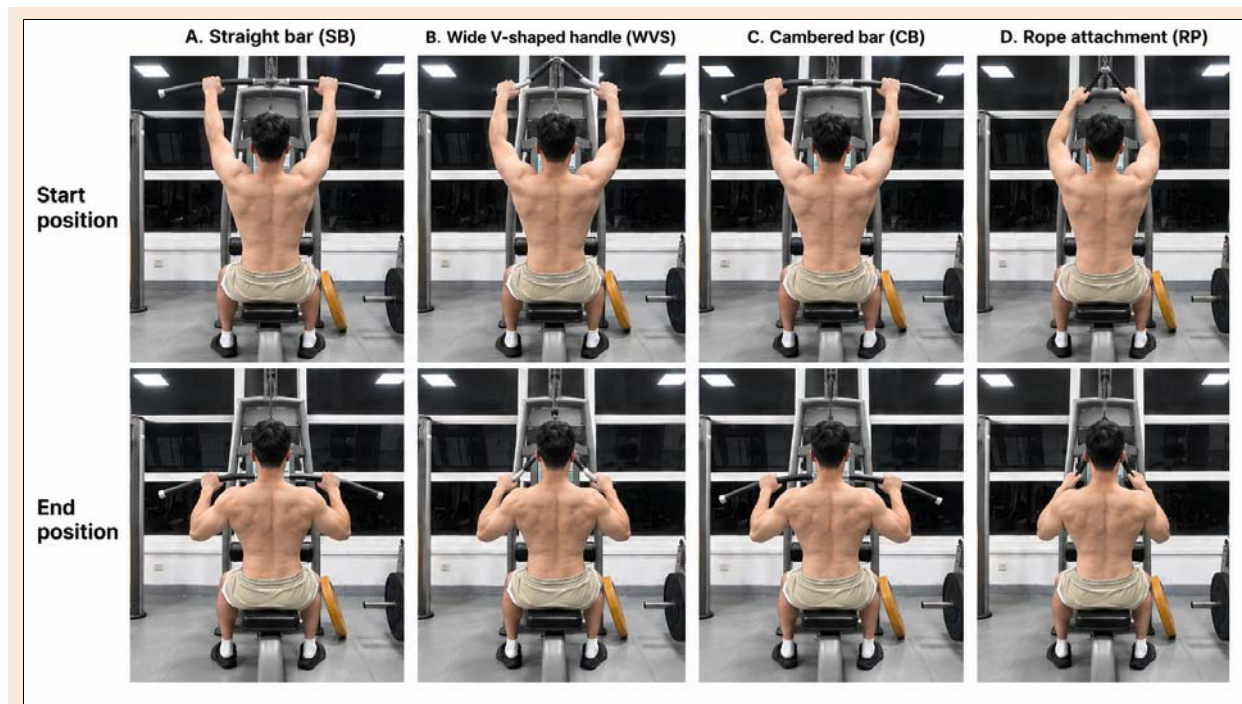
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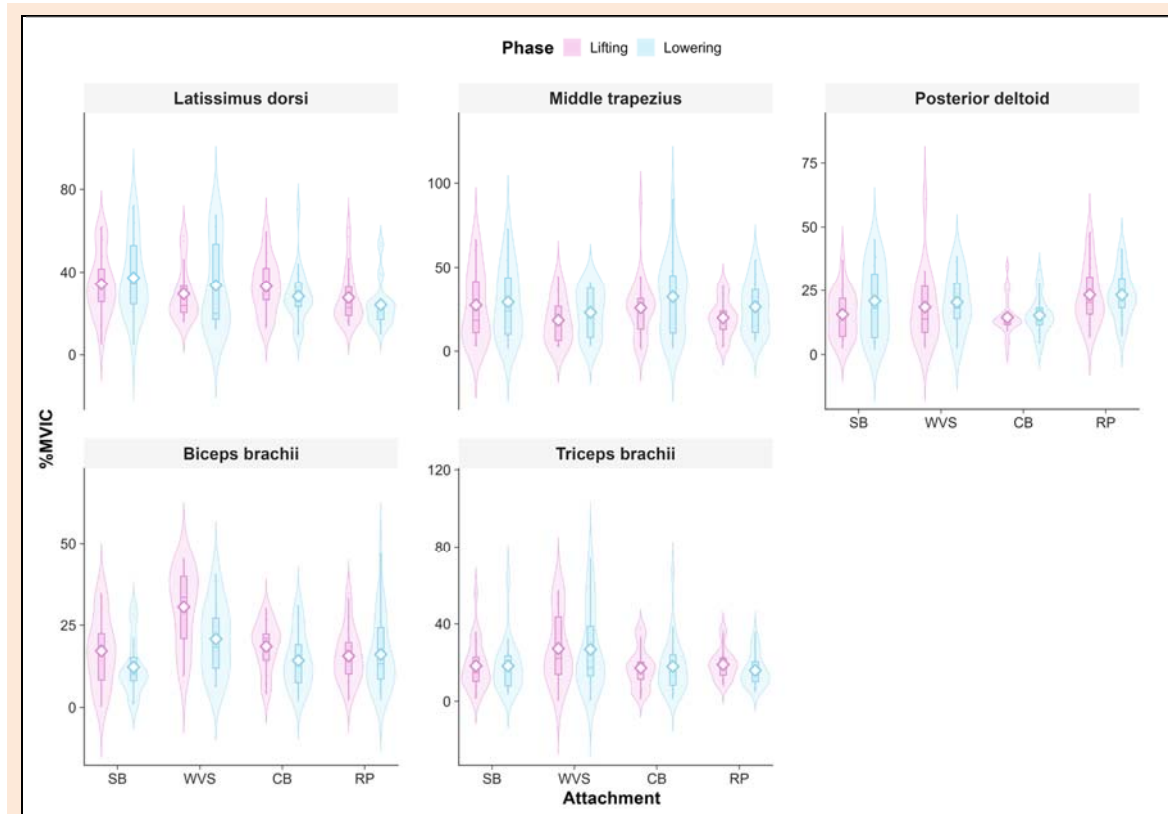
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## Supplementary Materials



**Supplementary Figure S1. Standardized start and end positions for the front lat pulldown across attachment conditions.** Photographs show representative standardized start and end positions using the actual experimental setup. Participants were seated with the thighs secured beneath the leg pad and the pelvis stabilized on the seat. The attachment was pulled in front of the body toward the upper- to mid-chest while the elbows were drawn downward without excessive backward displacement, and was then returned under control to the starting position. SB = straight bar; WVS = wide V-shaped handle; CB = cambered bar; RP = rope attachment.



**Supplementary Figure S2. Distribution of raw sEMG observations across attachment conditions and cadence-defined analytical intervals.** Raw observed sEMG amplitude (%MVIC) is shown for the cadence-defined lifting and lowering analytical intervals across straight bar (SB), wide V-shaped handle (WVS), cambered bar (CB), and rope (RP). These interval labels do not represent mechanically synchronized phase boundaries. Violin plots show distributions, boxplots show medians and interquartile ranges, and diamonds indicate means. Panels are ordered as latissimus dorsi, middle trapezius, posterior deltoid, biceps brachii, and triceps brachii. Pink denotes lifting; light blue denotes lowering.

**Supplementary Table S1. Type III model tests and robustness summary.**

| Muscle            | Analysis                     | Attachment<br>p | Phase<br>p | Attachment × phase<br>p | Interpretation                                     |
|-------------------|------------------------------|-----------------|------------|-------------------------|----------------------------------------------------|
| Latissimus dorsi  | Primary                      | 0.063           | 0.373      | 0.046                   | Small interaction in primary model                 |
| Latissimus dorsi  | Repetition positions 1 and 2 | 0.063           | 0.373      | 0.046                   | Similar to primary                                 |
| Latissimus dorsi  | Complete cases               | 0.277           | 0.369      | 0.075                   | Interaction attenuated; interpret cautiously       |
| Middle trapezius  | Primary                      | 0.061           | < 0.001    | 0.761                   | Phase effect retained in sensitivity analyses      |
| Middle trapezius  | Repetition positions 1 and 2 | 0.106           | < 0.001    | 0.171                   | Robust                                             |
| Middle trapezius  | Complete cases               | 0.266           | 0.015      | 0.097                   | Robust                                             |
| Posterior deltoid | Primary                      | 0.003           | 0.118      | 0.275                   | Attachment effect retained in sensitivity analyses |
| Posterior deltoid | Repetition positions 1 and 2 | 0.003           | 0.086      | 0.184                   | Robust                                             |
| Posterior deltoid | Complete cases               | 0.035           | 0.272      | 0.445                   | Robust                                             |
| Biceps brachii    | Primary                      | < 0.001         | < 0.001    | < 0.001                 | Robust attachment, phase, and interaction effects  |
| Biceps brachii    | Repetition positions 1 and 2 | < 0.001         | < 0.001    | < 0.001                 | Robust                                             |
| Biceps brachii    | Complete cases               | < 0.001         | < 0.001    | < 0.001                 | Robust                                             |
| Triceps brachii   | Primary                      | 0.025           | 0.424      | 0.412                   | Attachment effect in primary model                 |
| Triceps brachii   | Repetition positions 1 and 2 | 0.025           | 0.424      | 0.412                   | Similar to primary                                 |
| Triceps brachii   | Complete cases               | 0.459           | 0.279      | 0.018                   | Pattern changed; interpret cautiously              |

Values are p values from Type III tests with Satterthwaite approximation. The table summarizes whether the inferential pattern observed in the primary models was preserved in the two sensitivity analyses. This table should be used to interpret robustness across the primary, repetition positions 1 and 2, and complete-case analyses.

**Supplementary Table S2. Sample audit for the primary and sensitivity analysis datasets.**

| Analysis                     | Muscle            | Analytical-interval observations | Participants |
|------------------------------|-------------------|----------------------------------|--------------|
| Primary                      | Latissimus dorsi  | 174                              | 13           |
| Primary                      | Middle trapezius  | 171                              | 13           |
| Primary                      | Posterior deltoid | 181                              | 14           |
| Primary                      | Biceps brachii    | 171                              | 13           |
| Primary                      | Triceps brachii   | 178                              | 14           |
| Repetition positions 1 and 2 | Latissimus dorsi  | 174                              | 13           |
| Repetition positions 1 and 2 | Middle trapezius  | 169                              | 13           |
| Repetition positions 1 and 2 | Posterior deltoid | 179                              | 14           |
| Repetition positions 1 and 2 | Biceps brachii    | 171                              | 13           |
| Repetition positions 1 and 2 | Triceps brachii   | 178                              | 14           |
| Complete cases               | Latissimus dorsi  | 109                              | 7            |
| Complete cases               | Middle trapezius  | 110                              | 7            |
| Complete cases               | Posterior deltoid | 123                              | 8            |
| Complete cases               | Biceps brachii    | 124                              | 8            |
| Complete cases               | Triceps brachii   | 94                               | 6            |

Analytical-interval observations refer to the number of lifting or lowering sEMG observations entering each model. The complete-case analysis reflects a stricter subset requiring complete observations for all 4 attachment × 2 phase combinations within each muscle.

**Supplementary Table S3. Original repetition-position distribution and interquartile-range-based outlier-screening diagnostics.**

| Repetition position | Observations, n |
|---------------------|-----------------|
| 1                   | 446             |
| 2                   | 425             |
| 3                   | 4               |

Repetition position refers to the original position within the five-repetition set. The primary sEMG analysis retained the first two repetitions meeting the predefined technique, cadence, signal-quality, and analytical-window criteria; when an earlier repetition was unusable, the next eligible repetition was used. Only four retained analytical-interval observations were coded as repetition position 3, and none were coded as positions 4 or 5. The sensitivity analysis restricted to positions 1 and 2 therefore closely resembled the primary analysis.

| Muscle            | Phase    | Rows flagged by 1.5 × IQR rule | Flagged (%) |
|-------------------|----------|--------------------------------|-------------|
| Latissimus dorsi  | Lifting  | 0                              | 0.0         |
| Latissimus dorsi  | Lowering | 5                              | 5.9         |
| Middle trapezius  | Lifting  | 2                              | 2.3         |
| Middle trapezius  | Lowering | 1                              | 1.2         |
| Posterior deltoid | Lifting  | 4                              | 4.3         |
| Posterior deltoid | Lowering | 0                              | 0.0         |
| Biceps brachii    | Lifting  | 0                              | 0.0         |
| Biceps brachii    | Lowering | 0                              | 0.0         |
| Triceps brachii   | Lifting  | 6                              | 6.5         |
| Triceps brachii   | Lowering | 6                              | 7.1         |

Interquartile-range-based summaries were generated as diagnostic checks only and were not used as automatic exclusion criteria in the reanalysis.

**Supplementary Table S4. Final model structures used for primary inference.**

| Muscle            | Primary model structure                                 | Model-checking note                                                                                                                                                                                                                                                                            |
|-------------------|---------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Latissimus dorsi  | sEMG amplitude ~ attachment × phase + (1   participant) | Participant-level random effects were retained to account for repeated observations. More complex random-effects structures were considered and simplified when necessary after singular-fit diagnostics. Inference should be based on Type III tests and estimated marginal mean comparisons. |
| Middle trapezius  | sEMG amplitude ~ attachment × phase + (1   participant) | Participant-level random effects were retained to account for repeated observations. More complex random-effects structures were considered and simplified when necessary after singular-fit diagnostics. Inference should be based on Type III tests and estimated marginal mean comparisons. |
| Posterior deltoid | sEMG amplitude ~ attachment × phase + (1   participant) | Participant-level random effects were retained to account for repeated observations. More complex random-effects structures were considered and simplified when necessary after singular-fit diagnostics. Inference should be based on Type III tests and estimated marginal mean comparisons. |
| Biceps brachii    | sEMG amplitude ~ attachment × phase + (1   participant) | Participant-level random effects were retained to account for repeated observations. More complex random-effects structures were considered and simplified when necessary after singular-fit diagnostics. Inference should be based on Type III tests and estimated marginal mean comparisons. |
| Triceps brachii   | sEMG amplitude ~ attachment × phase + (1   participant) | Participant-level random effects were retained to account for repeated observations. More complex random-effects structures were considered and simplified when necessary after singular-fit diagnostics. Inference should be based on Type III tests and estimated marginal mean comparisons. |

This table clarifies that repetition-level observations were modelled with participant-level clustering rather than treated as independent participants.

### Additional robustness analyses addressing cadence, temporal uncertainty, and absolute load

Temporal robustness analyses used the same participant-specific fixed 20% right-LD onset criterion as the primary analysis (50-ms moving RMS; cross-condition maximum reference; 50-ms persistence) and do not imply hardware synchronization. Kinematic active-motion durations reported below were derived independently from motion capture and were not time-registered to individual sEMG samples

### Supplementary Table S5. Kinematic characterization of velocity-defined active-motion duration and between-attachment differences.

#### Panel A. Velocity-defined active-motion durations in participants with both motion-capture and sEMG data

| Metric | Repetitions, n | Participants, n | Mean $\pm$ SD, s  | Median, s | Cluster-bootstrap 95% CI, s |
|--------|----------------|-----------------|-------------------|-----------|-----------------------------|
| Pull   | 89             | 13              | 1.477 $\pm$ 0.282 | 1.460     | 1.353 - 1.592               |
| Return | 89             | 13              | 1.434 $\pm$ 0.391 | 1.395     | 1.297 - 1.580               |
| Total  | 89             | 13              | 2.911 $\pm$ 0.574 | 2.840     | 2.663 - 3.151               |

The analysis included 13 participants and 89 retained repetitions. Durations were derived from the velocity-based kinematic event algorithm and represent the active-motion portions of the pull and return. They are distinct from, and were not intended to reproduce, the complete nominal 2.0-second metronome-prescribed lifting or lowering intervals.

#### Panel B. Attachment-specific participant-level mean velocity-defined active-motion durations and complete-case comparisons

| Metric | SB, s             | WVS, s            | CB, s             | RP, s             | F(3, 30) | GG-corrected p | SB - WVS, s [95% CI] | Holm p |
|--------|-------------------|-------------------|-------------------|-------------------|----------|----------------|----------------------|--------|
| Pull   | 1.497 $\pm$ 0.227 | 1.381 $\pm$ 0.212 | 1.462 $\pm$ 0.275 | 1.622 $\pm$ 0.442 | 2.860    | 0.090          | 0.116 [0.011, 0.221] | 0.201  |
| Return | 1.515 $\pm$ 0.252 | 1.277 $\pm$ 0.282 | 1.504 $\pm$ 0.571 | 1.459 $\pm$ 0.428 | 1.140    | 0.343          | 0.238 [0.095, 0.381] | 0.025  |
| Total  | 3.012 $\pm$ 0.431 | 2.658 $\pm$ 0.433 | 2.965 $\pm$ 0.788 | 3.081 $\pm$ 0.667 | 2.237    | 0.130          | 0.354 [0.176, 0.533] | 0.008  |

Complete-case n = 11. Attachment values are mean  $\pm$  SD of participant-level mean velocity-defined active-motion durations. GG = Greenhouse-Geisser. Pairwise p values are Holm-adjusted. SB = straight bar; WVS = wide V-shaped handle; CB = cambered bar; RP = rope.

### Supplementary Table S6. Robustness of principal sEMG contrasts after adjustment for participant-by-attachment mean velocity-defined active-motion duration.

| Muscle / contrast                 | Primary-analysis estimate | Unadjusted estimate (same sample) | Duration-adjusted estimate | Adjusted 95% CI | Change after adjustment |
|-----------------------------------|---------------------------|-----------------------------------|----------------------------|-----------------|-------------------------|
| PD: RP - CB (marginal)            | 7.96                      | 7.77                              | 7.49                       | 4.53 - 10.46    | -0.28 (3.6%)            |
| BB: WVS - SB, lifting             | 10.95                     | 12.27                             | 12.29                      | 7.94 - 16.63    | +0.02 (0.2%)            |
| BB: WVS - CB, lifting             | 10.59                     | 11.83                             | 11.84                      | 7.51 - 16.16    | +0.01 (0.1%)            |
| BB: WVS - RP, lifting             | 15.66                     | 16.56                             | 16.61                      | 12.37 - 20.85   | +0.05 (0.3%)            |
| MT: lowering - lifting (marginal) | 6.15                      | 5.62                              | 5.67                       | 2.19 - 9.16     | +0.06 (1.0%)            |

Duration-adjusted estimates were obtained from the attachment  $\times$  phase mixed-effects model with participant  $\times$  attachment mean velocity-defined pull/return active-motion duration entered as the corresponding interval-specific covariate (pull duration for the lifting analytical interval and return duration for the lowering analytical interval). The kinematic durations were not time-registered to individual sEMG repetitions. Unadjusted estimates used the same sEMG observations without the duration covariate. Values are reported in the same outcome units as the primary analysis.

### Supplementary Table S7. Temporal-window perturbation analysis of sEMG contrasts.

| Muscle / contrast                | -500 ms             | -250 ms             | 0 ms                 | +250 ms             | +500 ms             |
|----------------------------------|---------------------|---------------------|----------------------|---------------------|---------------------|
| PD: RP - CB                      | 6.77 [4.27, 9.27]   | 5.82 [3.40, 8.24]   | 4.30 [1.26, 7.33]    | 4.01 [0.62, 7.40]   | 5.91 [2.28, 9.53]   |
| BB: WVS - SB, lifting            | 12.08 [6.71, 17.46] | 11.41 [5.99, 16.83] | 7.61 [1.74, 13.49]   | 4.70 [-1.07, 10.47] | 4.45 [-1.55, 10.44] |
| BB: WVS - CB, lifting            | 12.75 [7.40, 18.10] | 11.56 [6.17, 16.96] | 9.40 [3.55, 15.24]   | 5.71 [-0.04, 11.45] | 4.65 [-1.32, 10.61] |
| BB: WVS - RP, lifting            | 14.18 [9.07, 19.29] | 14.26 [9.11, 19.42] | 12.36 [6.78, 17.95]  | 9.33 [3.84, 14.81]  | 8.56 [2.87, 14.26]  |
| MT: lowering - lifting           | 10.47 [6.41, 14.54] | 12.80 [9.04, 16.57] | 13.91 [10.37, 17.44] | 13.44 [9.61, 17.27] | 9.67 [5.35, 13.99]  |
| TB: WVS - CB                     | 6.70 [1.97, 11.44]  | 6.28 [1.50, 11.06]  | 5.32 [0.44, 10.19]   | 4.76 [-0.47, 9.99]  | 5.15 [-0.60, 10.91] |
| TB: WVS - RP                     | 7.43 [2.80, 12.06]  | 6.96 [2.29, 11.64]  | 5.58 [0.82, 10.35]   | 4.32 [-0.81, 9.45]  | 2.35 [-3.27, 7.97]  |
| LD: SB - RP, lowering            | 4.75 [-1.35, 10.85] | 5.00 [-1.27, 11.26] | 5.27 [-0.99, 11.53]  | 2.88 [-3.15, 8.92]  | 6.41 [0.08, 12.75]  |
| LD: lifting - lowering within CB | 10.39 [4.64, 16.15] | 14.56 [8.65, 20.48] | 14.82 [8.91, 20.73]  | 13.59 [7.89, 19.28] | 11.65 [5.67, 17.63] |
| LD: lifting - lowering within RP | 3.63 [-2.01, 9.27]  | 6.77 [0.97, 12.57]  | 8.20 [2.41, 13.99]   | 9.73 [4.15, 15.31]  | 10.80 [4.94, 16.66] |

Values are model-estimated contrasts [95% CI] using the participant-specific fixed 20% right-LD EMG-defined activity-onset criterion (50-ms moving RMS envelope; at least 50-ms threshold persistence) and 1-second lifting/lowering analytical windows shifted by the indicated amount. The 0-ms condition represents the reference placement of the 1-second sensitivity window, not the primary full 2-second analytical interval; therefore, the 0-ms estimates are not expected to reproduce the primary-model estimates. The  $\pm 250$ - and  $\pm 500$ -ms conditions shift this same 1-second window earlier or later. For LD, attachment  $\times$  phase interaction p values were 0.305, 0.162, 0.143, 0.480, and 0.269 at -500, -250, 0, +250, and +500 ms, respectively. PD = posterior deltoid; BB = biceps brachii; MT = middle trapezius; TB = triceps brachii; LD = latissimus dorsi.

**Supplementary Table S8. Boundary-free nominal 4.0-second analytical-window analysis after removal of the lifting-to-lowering analytical boundary.**

**Panel A. Attachment omnibus tests in the boundary-free nominal 4.0-second analytical-window analysis.**

| Muscle | Rows, n | Participants, n | Conditions, n | Wald $\chi^2$ | df | p       |
|--------|---------|-----------------|---------------|---------------|----|---------|
| PD     | 86      | 14              | 46            | 13.75         | 3  | 0.003   |
| BB     | 82      | 13              | 44            | 25.05         | 3  | < 0.001 |
| TB     | 88      | 14              | 47            | 10.01         | 3  | 0.018   |
| MT     | 83      | 13              | 43            | 13.71         | 3  | 0.003   |
| LD     | 84      | 13              | 45            | 4.72          | 3  | 0.194   |

Boundary-free models used a continuous nominal 4.0-second window beginning at the same participant-specific fixed 20% right-LD EMG-defined activity onset (50-ms moving RMS envelope; at least 50-ms threshold persistence), with attachment as a fixed effect and participant as a random intercept. The phase term was not included. This analysis removes the lifting-to-lowering analytical boundary but does not identify the true mechanical cycle.

**Panel B. Prespecified attachment contrasts in the boundary-free nominal 4.0-second analytical-window analysis.**

| Muscle / contrast | Boundary-free 4.0-s estimate [95% CI] | Bonferroni-adjusted p |
|-------------------|---------------------------------------|-----------------------|
| PD: RP-CB         | 7.15 [3.15, 11.15]                    | 0.003                 |
| BB: WVS-SB        | 2.22 [-0.85, 5.29]                    | 0.937                 |
| BB: WVS-CB        | 1.34 [-1.81, 4.48]                    | 1.000                 |
| BB: WVS-RP        | 6.70 [3.63, 9.77]                     | < 0.001               |
| TB: WVS-CB        | 8.09 [2.80, 13.38]                    | 0.016                 |
| TB: WVS-RP        | 3.33 [-1.73, 8.40]                    | 1.000                 |

Bonferroni correction was applied across the six prespecified contrasts. The original middle-trapezius lifting-versus-lowering analytical-interval contrast is not estimable after removal of the phase term and therefore is not confirmed by this analysis. The LD boundary-free attachment omnibus test was not significant ( $p = 0.194$ ).

**Supplementary Table S9. Absolute-load-adjusted sensitivity analyses for principal sEMG findings.**

**Panel A. Principal contrasts before and after adjustment for absolute load**

| Muscle / contrast                 | Unadjusted estimate [95% CI] | Load-adjusted estimate [95% CI] | Change after adjustment | Direction retained |
|-----------------------------------|------------------------------|---------------------------------|-------------------------|--------------------|
| PD: RP - CB (marginal)            | 7.96 [5.16, 10.76]           | 13.27 [8.57, 17.96]             | +5.31 (66.7%)           | Yes                |
| BB: WVS - SB, lifting             | 10.95 [6.93, 14.97]          | 12.32 [7.75, 16.90]             | +1.37 (12.6%)           | Yes                |
| BB: WVS - CB, lifting             | 10.59 [6.59, 14.59]          | 11.42 [7.21, 15.63]             | +0.83 (7.8%)            | Yes                |
| BB: WVS - RP, lifting             | 15.67 [11.84, 19.49]         | 14.17 [9.68, 18.67]             | -1.49 (9.5%)            | Yes                |
| MT: lowering - lifting (marginal) | 6.15 [2.83, 9.47]            | 6.13 [2.81, 9.46]               | -0.02 (0.3%)            | Yes                |

Contrast estimates are in %MVIC. Change is the load-adjusted minus unadjusted estimate; the percentage in parentheses is the absolute percentage change relative to the unadjusted estimate. The load-adjusted model added actual experimental load as a covariate to the attachment  $\times$  phase mixed-effects model with participant retained as a random intercept. Secondary triceps-brachii contrasts also retained the same direction after adjustment: WVS - CB = 9.61 [4.16, 15.06] and WVS - RP = 8.70 [2.77, 14.63].

**Panel B. Fixed-effect terms for absolute load and the load  $\times$  phase sensitivity model**

| Muscle | Absolute-load $\beta$ | p     | Load $\times$ phase $\beta$ | p     |
|--------|-----------------------|-------|-----------------------------|-------|
| PD     | 0.757                 | 0.006 | -0.118                      | 0.829 |
| BB     | 0.332                 | 0.219 | 0.874                       | 0.095 |
| MT     | -0.408                | 0.313 | 0.415                       | 0.600 |
| TB     | 0.097                 | 0.818 | -0.304                      | 0.711 |
| LD     | -0.678                | 0.045 | -0.060                      | 0.928 |

Absolute-load  $\beta$  is the fixed-effect coefficient for the actual experimental load covariate in the load-adjusted model. The load  $\times$  phase coefficient is from an additional sensitivity model containing the corresponding interaction term. Absolute load was associated with posterior-deltoid and latissimus-dorsi sEMG ( $p = 0.006$  and  $p = 0.045$ , respectively), whereas no load  $\times$  phase interaction reached statistical significance (all  $p \geq 0.095$ ). These models are robustness analyses only; because absolute load is structurally related to attachment-specific 1RM, covariate adjustment does not identify a load-independent causal effect of attachment geometry. PD = posterior deltoid; BB = biceps brachii; MT = middle trapezius; TB = triceps brachii; LD = latissimus dorsi; WVS = wide V-shaped handle; SB = straight bar; CB = cambered bar; RP = rope.

**Supplementary Table S10. Descriptive normalized sEMG amplitude across attachment conditions and cadence-defined analytical intervals.**

| Muscle | Analytical interval | SB              | WVS             | CB              | RP              |
|--------|---------------------|-----------------|-----------------|-----------------|-----------------|
| LD     | Lifting             | 34.2 $\pm$ 15.4 | 29.3 $\pm$ 13.1 | 33.0 $\pm$ 12.9 | 27.5 $\pm$ 12.7 |
| LD     | Lowering            | 37.3 $\pm$ 18.4 | 33.4 $\pm$ 21.3 | 28.1 $\pm$ 12.9 | 24.0 $\pm$ 11.3 |
| MT     | Lifting             | 27.3 $\pm$ 21.0 | 18.3 $\pm$ 13.6 | 25.6 $\pm$ 18.1 | 19.8 $\pm$ 11.0 |
| MT     | Lowering            | 29.0 $\pm$ 21.2 | 22.9 $\pm$ 14.2 | 32.2 $\pm$ 22.3 | 26.2 $\pm$ 14.9 |
| PD     | Lifting             | 15.6 $\pm$ 9.1  | 18.5 $\pm$ 14.3 | 14.5 $\pm$ 7.3  | 23.3 $\pm$ 11.5 |
| PD     | Lowering            | 20.9 $\pm$ 13.7 | 20.4 $\pm$ 11.1 | 15.2 $\pm$ 7.7  | 23.2 $\pm$ 9.3  |
| BB     | Lifting             | 17.1 $\pm$ 10.5 | 30.5 $\pm$ 11.7 | 18.5 $\pm$ 7.5  | 15.6 $\pm$ 8.3  |
| BB     | Lowering            | 12.3 $\pm$ 8.7  | 20.8 $\pm$ 10.7 | 14.3 $\pm$ 8.3  | 16.1 $\pm$ 10.9 |
| TB     | Lifting             | 18.3 $\pm$ 12.6 | 27.3 $\pm$ 18.2 | 17.2 $\pm$ 10.5 | 19.0 $\pm$ 7.9  |
| TB     | Lowering            | 18.3 $\pm$ 13.9 | 26.8 $\pm$ 21.1 | 18.0 $\pm$ 13.9 | 16.0 $\pm$ 8.3  |

Values are mean  $\pm$  SD after averaging retained repetitions within each participant, muscle, attachment, and analytical-interval combination and are expressed as percentages of maximal voluntary isometric contraction (%MVIC). Lifting and lowering denote the cadence-defined analytical windows used for sEMG quantification and should not be interpreted as mechanically synchronized phase boundaries. LD = latissimus dorsi; MT = middle trapezius; PD = posterior deltoid; BB = biceps brachii; TB = triceps brachii; SB = straight bar; WVS = wide V-shaped handle; CB = cambered bar; RP = rope.