Original Research

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Understanding Bench Press Biomechanics—The Necessity of Measuring Lateral Barbell Forces

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Abstract

Mausehund, L, Werkhausen, A, Bartsch, J, and Krosshaug, T. Understanding bench press biomechanics—The necessity of measuring lateral barbell forces. *J Strength Cond Res* 36(10): 2685–2695, 2022—The purpose of this study was to advance the expertise of the bench press exercise by complementing electromyographic (EMG) with net joint moment (NJM) and strength normalized NJM (nNJM) measurements, thus establishing the magnitude of the elbow and shoulder muscular loads and efforts. Normalized NJMs were determined as the ratio of the bench press NJMs to the maximum NJMs produced during maximum voluntary isokinetic contractions. Furthermore, we wanted to assess how changes in grip width and elbow positioning affected elbow and shoulder NJMs and nNJMs, and muscle activity of the primary movers. Thirty-five strength-trained adults performed a 6–8 repetition maximum set of each bench press variation, while elbow and shoulder NJMs and EMG activity of 7 upper extremity muscles were recorded. The results show that all bench press variations achieved high elbow and shoulder muscular efforts. A decrease in grip width induced larger elbow NJMs, and larger EMG activity of the lateral head of the triceps brachii, anterior deltoid, and clavicular head of the pectoralis major ($p \leq 0.05$). An increase in grip width elicited larger shoulder NJMs and nNJMs, and larger EMG activity of the abdominal head of the pectoralis major ($p \leq 0.05$). In conclusion, all bench press variations may stimulate strength gains and hypertrophy of the elbow extensors and shoulder flexors and horizontal adductors. However, greater adaptations of the elbow extensors and shoulder flexors may be expected when selecting narrower grip widths, whereas wider grip widths may induce greater adaptations of the shoulder horizontal adductors.

Key Words: net joint moment, EMG, muscle activity, grip width, muscular effort

Introduction

The bench press is one of the most frequently used strength training exercises to develop upper-body strength, power, and hypertrophy and is commonly integrated in resistance training programs, both for sport performance (33), general fitness, as well as for injury prevention and rehabilitation (16). For the proper understanding of bench press biomechanics and to infer the neuromuscular adaptations which may be elicited by this exercise and its variations, measurements of muscular loads and muscular efforts are crucial. Measures of muscular loads, e.g., net joint moments (NJMs), describe the absolute net loading on muscle groups, whereas measures of muscular efforts, e.g., normalized electromyography (EMG) and strength normalized NJMs (nNJMs), describe the relative loading on muscle groups. Our current knowledge on bench press biomechanics is mainly based on EMG studies. However, considering the limitations associated with EMG, its sole use as an indicator of muscular effort is insufficient (36). Complementing EMG with NJM and nNJM measurements is important for enhancing the understanding of exercise biomechanics.

Many studies report NJMs during performance of lower-body strength exercises, such as the deadlift and the squat (34). However, there is a scarcity of research on upper-body strength exercises, which may be related to the challenges arising from measuring forces acting on the upper extremities. To the best of our knowledge, there are only 3 studies measuring NJMs during the bench press (6,23,37), in all of which the external forces used to calculate the NJMs were assumed to act vertically downward from the point of force application. However, by using an instrumented barbell, more recent research has documented the presence of lateral forces during the bench press, which accounted for approximately 25% of the vertical forces (10). These lateral forces will impact the moment arms and NJMs and must therefore be taken account of.

NJMs provide information regarding absolute muscular loads but can hardly be used to make inferences about potential strength training adaptations. To make such inferences possible, NJMs must be expressed relative to the maximal NJM produced during a maximal voluntary contraction, thereby establishing nNJMs (3,5). To the best of our knowledge, only one study has reported nNJMs for strength exercises, specifically for the squat (3), yet no such research exists for the bench press.

Selecting appropriate exercises and exercise variations is an important part of resistance training program design and involves matching the demands of the exercise with the specific needs of the individual. This requires a thorough understanding of the mechanical demands which the exercise imposes on the musculoskeletal system. One of the most common exercise variations of the bench press involves the use of different grip widths. A good understanding of the biomechanical alterations which occur with changes of grip width is important for appropriate exercise

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prescription. However, long-term training studies on this topic are missing, and acute biomechanical research is limited and conflicting. Whereas some EMG studies found no difference in muscle activity of the triceps brachii across grip widths (9,29), others reported larger activity with narrower grip widths (1,4,21). The narrow grip width resulted also in higher activity of the clavicular head of the pectoralis major in one study (1), yet 3 other studies found no effect of grip width (9,21,29). Whereas the sternocostal head of the pectoralis major was not affected by grip width in 2 studies (1,29), Lehman (21) found differences in favor of a wide grip width. Conflicting results may be related to different methodological approaches, few subjects and the limitations inherent in EMG measurements (8). In addition, previous studies lack standardization and description of elbow positioning during the narrow grip bench press, which can be performed with either the elbows close to the body or away from the body. This in turn is likely to impact the biomechanics of the exercise.

The first purpose of this study was to advance the expertise of the bench press exercise by complementing EMG with NJM and nNJM measurements, thus providing a thorough and comprehensive biomechanical analysis and establishing the magnitude of the elbow and shoulder muscular loads and efforts. The second purpose was to assess the effect of 4 different bench press exercise variations on kinematics, kinetics, and muscle activity of the upper extremities. Specifically, we wanted to analyze how changes in grip width and elbow positioning affected elbow and shoulder NJMs and nNJMs, and normalized EMG activity of the primary movers.

Methods

Experimental Approach to the Problem

We used a cross-sectional, within-subjects design to assess kinematics, kinetics, and muscle activity of the upper extremities during execution of the bench press exercise with different grip widths and elbow positions (Figure 1). All subjects completed 2 test sessions, separated by at least 72 hours. During the first session, 3–10 repetition maximum (RM) was tested for all bench press variations, followed by familiarization with an isokinetic dynamometer. During the second session, synchronized kinematic, kinetic, and EMG data were collected during a 6–8RM set of each exercise variation. Next, the subjects conducted maximum voluntary isokinetic contractions (MVICs) for the elbow and shoulder joint. To allow for comparisons to be made across exercises and subjects, the same relative load (6-8RM, i.e., approximately 80–85% of 1RM) was applied to all exercises. Subjects were instructed to refrain from any upper-body resistance training for 48 hours before testing. Both sessions were supervised by a physical therapist and a research assistant.

Subjects

Thirty-five healthy adults, including 16 women and 19 men, participated in this study (Table 1). Female and male subjects were required to be able to lift at least 0.7 times and 1.0 times their body mass in the bench press, respectively. In addition, all subjects had to be engaged in regular resistance training including the bench press, for at least 6 months before data collection. Both powerlifters (n = 13) and recreational strength-trained individuals (n = 22) were included. Subjects were excluded if they had acute musculoskeletal injuries or pain, or if they failed to perform the bench press variations in the prescribed manner. The study was approved by the ethical committee of the Norwegian School of Sport Science, and all subjects signed a written informed consent form before inclusion. The study conformed to the latest revision of the Declaration of Helsinki.

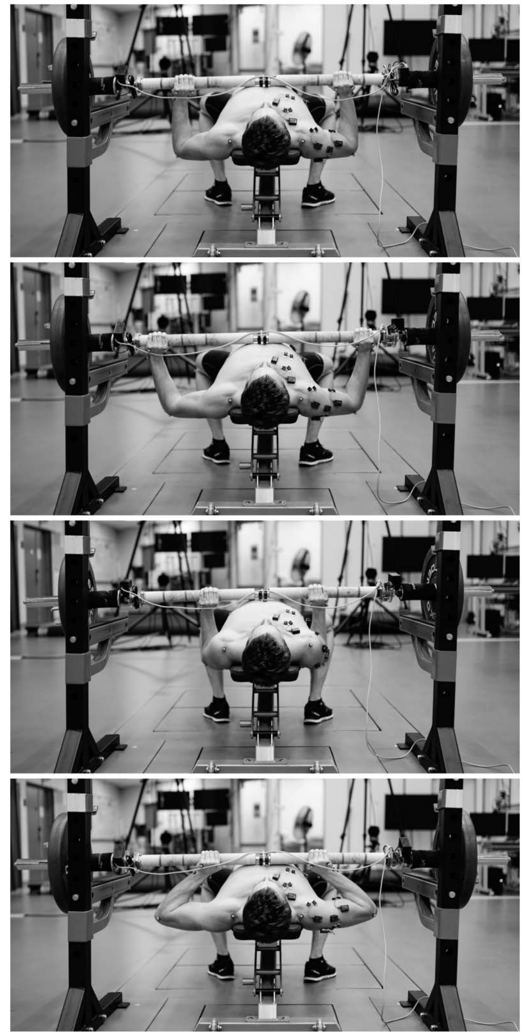

Figure 1. Bench press exercise variations. From top to bottom: medium grip width (BPM), wide grip width (BPW), narrow grip width keeping the elbows close to the body (BPNI), and narrow grip width keeping the elbows away from the body (BPNO).

Procedures

The first test session started with collecting anthropometric data, including height, biacromial distance, and arm length, followed by a demonstration of the testing criteria and standardized execution of each exercise variation. Thereafter, subjects performed a specific bench press warm-up, progressing from 10 to 20 repetitions with barbell load alone, to 10 repetitions at 50% of their expected 6RM, 4 repetitions at 70%, 2 repetitions at 80%, and 1 repetition at 90% (29). All warm-up sets were performed with the medium grip width. After the warm-up, 3–10RM was tested for all bench press variations, i.e., barbell load was adjusted until the maximum load was determined that could be lifted with correct technique for 3–10 repetitions. Three–five minutes of rest was provided between RM trials and at least 5 minutes between

Table 1
Subject characteristics (n = 35).*

Descriptive	Mean ± *SD*	Range
Age (y)	31.4 ± 10.4	19–58
Height (m)	1.71 ± 0.09	1.50–1.87
Body mass (kg)	79.9 ± 16.0	55.3–123.3
Biacromial distance (m)	0.36 ± 0.03	0.30–0.41
No. of resistance training sessions†	4.1 ± 1.1	1.5–6.0
No. of bench press sessions†	2.3 ± 1.3	0.3–6.0
1RM‡ to body mass ratio	1.22 ± 0.28	0.74–1.84

*1RM = 1 repetition maximum.
†Number of sessions per week during the last 6 months.
‡Estimated 1 repetition maximum (RM) for the medium grip width.

exercise variations. Exercise sequence was randomized for each subject. At the conclusion of the first test session, subjects were familiarized with an isokinetic dynamometer. Both an elbow extension and shoulder horizontal adduction movement were performed with 3 sets of 1 repetition each and gradually increasing effort (approximately 50, 80, and 100% of maximal effort, respectively).

The second test session started with attaching reflective markers and surface electrodes. Subjects wore their preferred footwear, shorts, or tights and, in addition, women a sports bra. After a static calibration trial, subjects repeated the specific bench press warm-up from the first test session. Subsequently, RM trials were conducted with the subjects' estimated 7RM loads, calculated using the bench press specific regression equation proposed by Reynolds et al. (27). If lifting criteria were met and a 6–8RM was accomplished, the subjects continued with the next exercise variation. If the exercise was not performed in the prescribed manner or if the number of repetitions was outside the 6–8RM range, the trial was repeated with the load adjusted when necessary.

Finally, MVIC testing was conducted to normalize the NJM and EMG measurements from the bench press to a maximal reference value. We tested 2 joints of the right upper extremity (see Figure, Supplemental Digital Content 1, http://links.lww.com/JSCR/A245): For the elbow joint, subjects were fastened in a sitting position and instructed to produce maximal concentric elbow extension torque from 135° to 0° elbow flexion with the forearm in a neutral position. The MVIC for the shoulder joint was acquired with subjects fastened in a supine position producing maximal concentric shoulder horizontal adduction torque from −20° to 90° shoulder horizontal adduction with the forearm in a supinated position. The movement order was counterbalanced across subjects. For each movement, the subjects started with 2 warm-up sets with increasing effort (approximately 50 and 80% of maximal effort, respectively), comprising 2 repetitions each. Next, 2 sets with maximal effort and 1 repetition each were performed, followed by a passive gravity correction measurement. 2 minutes of rest was provided between trials and test positions (11). In accordance with previous research (11) and to resemble average bench press speed, movement speed was set to $60°\cdot s^{-1}$.

Exercise Description. Four different bench press exercise variations, including 3 different grip widths and 2 elbow positions, were performed (Figure 1). To provide comparable upper-body configurations across subjects with various anthropometrics, the inner angle between the extended arm and the barbell (AB-angle) at the top position of the bench press exercise was used to standardize the grip widths. The first (BPM) and second (BPW) bench press variation were performed with a medium (75° AB-angle) and wide grip width (65° AB-angle), respectively. For the third variation (BPNI), a narrow grip width (85° AB-angle) was selected, and the elbows were kept close to the body. For the last variation (BPNO), the same grip width was chosen, but the elbows were kept away from the body, with a shoulder abduction angle of approximately 45° at the bottom position of the lift. Lifting criteria required all repetitions to be performed with a consistent pace through the whole range of motion (ROM), without stop or bouncing the barbell off the chest. The buttocks were to be kept in constant contact to the bench and the feet placed against the floor. To better mimic typical training conditions, exercise velocity was not predetermined. No performance enhancing lifting equipment was allowed. A bench press rack with safety bars and 2 spotters provided safety during all RM sets.

Measurements and Data Processing. All measurements were synchronously collected through a 16-bit analog-to-digital conversion board (USB-2533; Measurement Computing Corporation, Norton, MA), integrated to Qualisys Track Manager (version 2019.3; Qualisys AB, Gothenburg, Sweden) and further processed in Matlab (version R2019a; MathWorks Inc., Natick, MA).

Kinematics. Three-dimensional kinematic data were recorded with a 16-camera motion capture system (Oqus 400/700; Qualisys AB) sampling at 150 Hz. Twenty-eight reflective markers (12.5–19 mm diameter) were placed bilaterally over the following anatomical landmarks (2): the heads of the second and fifth metacarpal bone, the radial and ulnar styloid, the medial and lateral epicondyle of the humerus, the most dorsal point on the acromioclavicular joint, the deepest point of the incisura jugularis, the xiphoid process, the anterior superior iliac spine, the greater trochanter, the lateral epicondyle of the femur, the lateral malleolus, the shoe over the fifth metatarsal bone, and both ends of the barbell (see Figure, Supplemental Digital Content 2, http://links.lww.com/JSCR/A246). To ensure consistency, the same trained physical therapist was responsible for placing the markers on all subjects.

The glenohumeral joint center location was calculated using the regression equation proposed by Rab et al. (25), which has been proven to be more reliable than other methods (24). Elbow and wrist joint centers were defined as the midpoints between the medial and lateral epicondyle markers, and the radial and ulnar styloid markers, respectively (39). Estimates of anatomical joint and segment angles were calculated in a 3-dimensional space from lines formed between the joint centers (14). The elbow flexion and shoulder horizontal adduction angles as well as the forearm angle were defined as depicted in Figure 2. The shoulder abduction angle was defined by the longitudinal axis of the humerus relative to the sagittal plane of the thorax and the arching angle by the sternum (i.e., the line through the incisura jugularis and xiphoid process markers) relative to the horizontal plane. Vertical barbell velocity was determined by numerical differentiation of the smoothed barbell position data through the process of finite difference calculus. As suggested by previous research (18), all kinematic and kinetic data were filtered using the same piecewise polynomial smoothing spline (computed from a smoothing parameter of 0.001).

Kinetics. Kinetic data were collected at 1500 Hz by means of a custom-made instrumented barbell (Figure 3) capable of

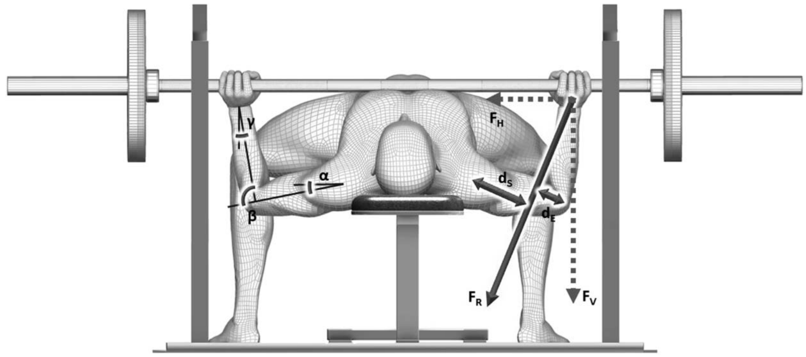

Figure 2. Animated bench press figure of one representative subject at the bottom position of the wide grip bench press. The left side illustrates the 3-dimensional joint and segment angles: α = shoulder horizontal adduction angle; β = elbow flexion angle; and γ = forearm angle. The right side illustrates the force vectors and moment arms: F_V = vertical force component; F_H = horizontal force component; F_R = resultant force vector; d_S = shoulder moment arm; d_E = elbow moment arm. Produced by MuscleAnimations.

measuring horizontal forces acting along the bar, and by 2 force plates (AMTI LG6-4-1, Watertown, MA) positioned underneath the bench and feet of the subject. Before subject recruitment, the instrumented barbell was calibrated, and its accuracy assessed (see Document, Supplemental Digital Content 3, http://links.lww.com/JSCR/A247). The vertical component (F_V) of the force that was exerted on the barbell was derived from the force plate measurements (35), whereas the horizontal component (F_H) was determined through the instrumented barbell (Figure 2). Both force components were added to produce a resultant force vector (F_R), which then was decomposed into a vector positioned in the forearm-upper arm plane and its orthogonal vector. The latter vector, creating shoulder rotation NJMs, was excluded from further analyses. The point of force application was defined to be located at the intersection between the barbell and the midline of the hand (i.e., the line through the wrist joint center and the midpoint of the metacarpal bone markers). The external NJMs about the shoulder and elbow joints were calculated as the products of the resultant force vector (F_R) and the respective moment arms (d_S and d_E).

Maximum voluntary isokinetic contraction strength testing was conducted in an isokinetic dynamometer (IsoMed 2000; D&R Ferstl GmbH, Hemau, Germany) using a sampling frequency of 600 Hz. The maximum isokinetic moment-angle curve, which was determined from the highest moment values achieved at each instantaneous angle of the 2 repetitions, was used for calculating nNJMs. Shoulder and elbow nNJMs were determined as the ratio of the NJMs generated during the bench press exercises to the maximum NJMs that could be produced during the MVIC tests (3). To provide joint angle specific nNJM data, NJMs from the bench press exercises and MVIC tests were matched for joint angle (3).

Electromyography. Raw EMG data were acquired at 1500 Hz by a 16-channel Noraxon TeleMyo Desktop Direct Transmission System (Noraxon USA, Inc., Scottsdale, AZ). Surface electrodes were attached to 7 muscles of the right upper extremity, including 2 heads of the triceps brachii, the anterior deltoid, 3 portions of the pectoralis major, and the biceps brachii (see Figure, Supplemental Digital Content 4, http://links.lww.com/JSCR/A248). Before positioning the electrodes, the skin was shaved and cleaned with isopropyl alcohol. Two pre-gelled Ag/AgCl electrodes (Covidien Kendall Disposable Surface EMG Electrodes; Bio-Medical Instruments, Clinton Township, MI; 10 mm^2 circular conductive area) were attached to each muscle belly, parallel to the muscle fibers' direction, and with an interelectrode distance of 20 mm (12). The exact positioning and orientation of the

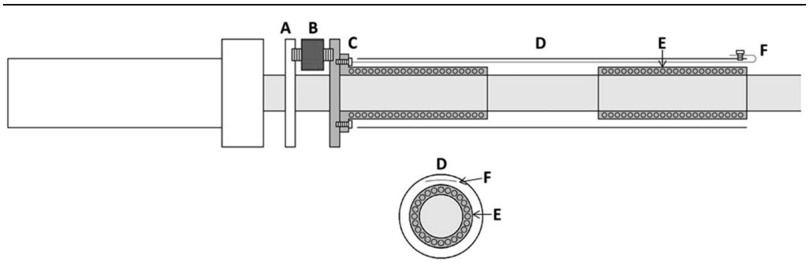

Figure 3. A schematic of the instrumented barbell capable of measuring lateral and medial forces acting along the bar at each hand. The longitudinal (top) and transverse (bottom) cross sections of the left barbell side are presented. The right side of the barbell is equivalent. The illustration is not to scale. A) Plastic ring fixed to the barbell; (B) force transducer fixed to a plastic ring on either side; (C) plastic ring and linear ball bearing rigidly attached to each other. Both have a frictionless but tight fit to the barbell and are only fixed to the force transducer; (D) metal sleeve covering the linear ball bearings; (E) second linear ball bearing; (F) strap connecting the metal sleeve (D) to the plastic ring (C), thus permitting medial forces to be measured.

electrodes for the triceps brachii (long and lateral head), biceps brachii, and anterior deltoid were in concordance with the recommendations of the SENIAM (Surface EMG for Non-Invasive Assessment of Muscles) project (12). The electrodes for the clavicular and sternocostal head of the pectoralis major were positioned according to Cram et al. (7). Based on anatomical studies (38), the electrodes for the abdominal head of the pectoralis major were placed on a line between the axillary fold and the mamilla, as close as possible to the mamilla but for female subjects slightly further lateral. Subsequent to fixating all electrodes, sensors, and cables, we inspected raw EMG baseline quality and performed manual muscle function tests to ensure EMG signal validity (12).

Differential preamplifiers (overall gain, 500; common mode rejection ratio, >100 dB; input impedance, >100 Mohm; root-mean-square baseline noise, <1 μV) were used to eliminate artifacts. Electromyography signals were digitally band-pass filtered using a zero-phase, recursive second-order Butterworth with high-pass and low-pass cut-off frequencies of 20 and 500 Hz, respectively (8), and smoothed by root mean square algorithm with a 100-millisecond sliding window. In addition, the average EMG envelope was calculated for each MVIC trial using a moving average filter with a 33 ms sliding window (31). Electromyography activity was normalized to the average of the peaks obtained during the 2 MVIC trials.

Statistical Analyses

All outcome measures were assessed over each entire bench press repetition. The start and end of the eccentric and concentric phases were determined using barbell velocity with thresholds of -0.015 and $0.015\ \mathrm{m{\cdot}s^{-1}}$, respectively (28). We averaged the outcome measures of the left and right side, and to avoid fatigue influencing the results, we used the first 3 repetitions of each subject as the basis for all analyses. Mean and peak values were extracted and used for statistical comparisons. All time series data were interpolated to 101 points (50 points for the eccentric phase, 1 point for the transition, and 50 points for the concentric phase), and ensemble average curves were calculated.

Statistical analyses were performed in IBM SPSS Statistics (Subscription version; IBM Corporation, Armonk, NY). Normality was assessed by the Shapiro-Wilk test and visual inspection of Q-Q plots. One-way repeated-measures analyses of variance were conducted to detect statistically significant differences in kinetic, kinematic, and EMG variables between the bench press variations. In cases where the assumption of sphericity was violated, as assessed by Mauchly's test of sphericity, a Greenhouse-Geisser correction was applied. Significant main effects were followed up by pairwise post-hoc comparisons with Bonferroni corrections. The level of significance was set a priori at $p \leq 0.05$. Results are presented as means ± *SD*. For main effects, adjusted *p*-values and partial eta squared (η_p^2) effect sizes are reported.

Results

We observed a difference in 6RM load among bench press variations ($p < 0.001$, $\eta_p^2 = 0.54$), with post-hoc tests revealing significantly greater loads being lifted during BPW (84.8 ± 30.8 kg) and BPM (84.0 ± 30.5 kg) compared with BPNO (76.9 ± 27.1 kg) and BPNI (75.8 ± 27.9 kg).

Kinetics

We found significant main effects for bench press condition for mean ($p < 0.001$, $\eta_p^2 = 0.32$) and peak ($p < 0.001$, $\eta_p^2 = 0.50$) elbow NJMs, as well as for mean ($p < 0.001$, $\eta_p^2 = 0.70$) and peak ($p < 0.001$, $\eta_p^2 = 0.78$) shoulder NJMs (Table 2). The largest elbow NJMs for BPW and BPM occurred in the middle of the eccentric and concentric phases, whereas for the narrow grip widths large elbow NJMs were also present at the lowest bar position (Figure 4). Peak shoulder NJMs were obtained at the bottom position of the lift for all bench press variations (Figure 4).

Elbow and shoulder moment arms differed statistically across bench press conditions (elbow mean: $p < 0.001$, $\eta_p^2 = 0.73$; elbow peak: $p < 0.001$, $\eta_p^2 = 0.72$; shoulder mean: $p < 0.001$, $\eta_p^2 = 0.42$; and shoulder peak: $p < 0.001$, $\eta_p^2 = 0.81$) (Table 2). For all exercise variations, elbow moment arms peaked in the middle of

Table 2

Mean and peak kinetic variables during performance of the bench press with different grip widths and elbow positioning.*†

	Medium	Wide	Narrow in	Narrow out
Elbow NJM, mean (Nm)	28.9 ± 11.2§¶	26.5 ± 10.2‡‖¶	29.4 ± 12.1§¶	31.4 ± 12.1‡§‖
Elbow NJM, peak (Nm)	37.7 ± 13.5§‖¶	35.4 ± 11.6‡‖¶	40.0 ± 15.1‡§¶	44.5 ± 15.6‡§‖
Shoulder NJM, mean (Nm)	66.6 ± 29.7§‖¶	69.6 ± 31.5‡‖¶	52.5 ± 24.4‡§¶	57.0 ± 24.9‡§‖
Shoulder NJM, peak (Nm)	123.0 ± 48.5§‖¶	135.2 ± 52.0‡‖¶	94.7 ± 38.3‡§	99.0 ± 40.0‡§
Elbow moment arm, mean (m)	0.072 ± 0.014§‖¶	0.064 ± 0.015‡‖¶	0.082 ± 0.014‡§	0.085 ± 0.014‡§
Elbow moment arm, peak (m)	0.092 ± 0.014§‖¶	0.084 ± 0.015‡‖¶	0.105 ± 0.014‡§	0.106 ± 0.016‡§
Shoulder moment arm, mean (m)	0.156 ± 0.025‖¶	0.155 ± 0.029‖	0.140 ± 0.023‡§¶	0.149 ± 0.025‡,‖
Shoulder moment arm, peak (m)	0.221 ± 0.023§‖¶	0.243 ± 0.030‡‖¶	0.195 ± 0.019‡§	0.198 ± 0.021‡§
Resultant force, mean (N)	406.6 ± 147.2§‖¶	425.5 ± 154.9‡‖¶	355.7 ± 131.0‡§¶	366.3 ± 130.1‡§‖
Lateral to vertical force ratio, mean	0.17 ± 0.06§‖¶	0.38 ± 0.07‡‖¶	0.01 ± 0.05‡§¶	−0.03 ± 0.06‡§‖
Elbow nNJM, mean (% MVIC)	64.1 ± 17.2	63.7 ± 17.4	60.6 ± 12.8	62.4 ± 13.4
Elbow nNJM, peak (% MVIC)	79.8 ± 19.8¶	78.6 ± 20.9¶	77.6 ± 14.6¶	88.1 ± 18.2‡§‖
Shoulder nNJM, mean (% MVIC)	80.5 ± 15.6‖	80.1 ± 18.5‖	70.4 ± 13.2‡§¶	76.7 ± 15.1‖
Shoulder nNJM, peak (% MVIC)	139.7 ± 24.4§‖¶	150.7 ± 30.8‡‖¶	112.2 ± 17.2‡§	117.9 ± 23.1‡§

*NJM, net joint moment; nNJM, strength normalized net joint moment; MVIC, maximum voluntary isokinetic contraction.
†Values are means ± *SD*.
‡Significant difference to medium grip width ($p \leq 0.05$).
§Significant difference to wide grip width ($p \leq 0.05$).
‖Significant difference to narrow grip width, elbows in ($p \leq 0.05$).
¶Significant difference to narrow grip width, elbows out ($p \leq 0.05$).

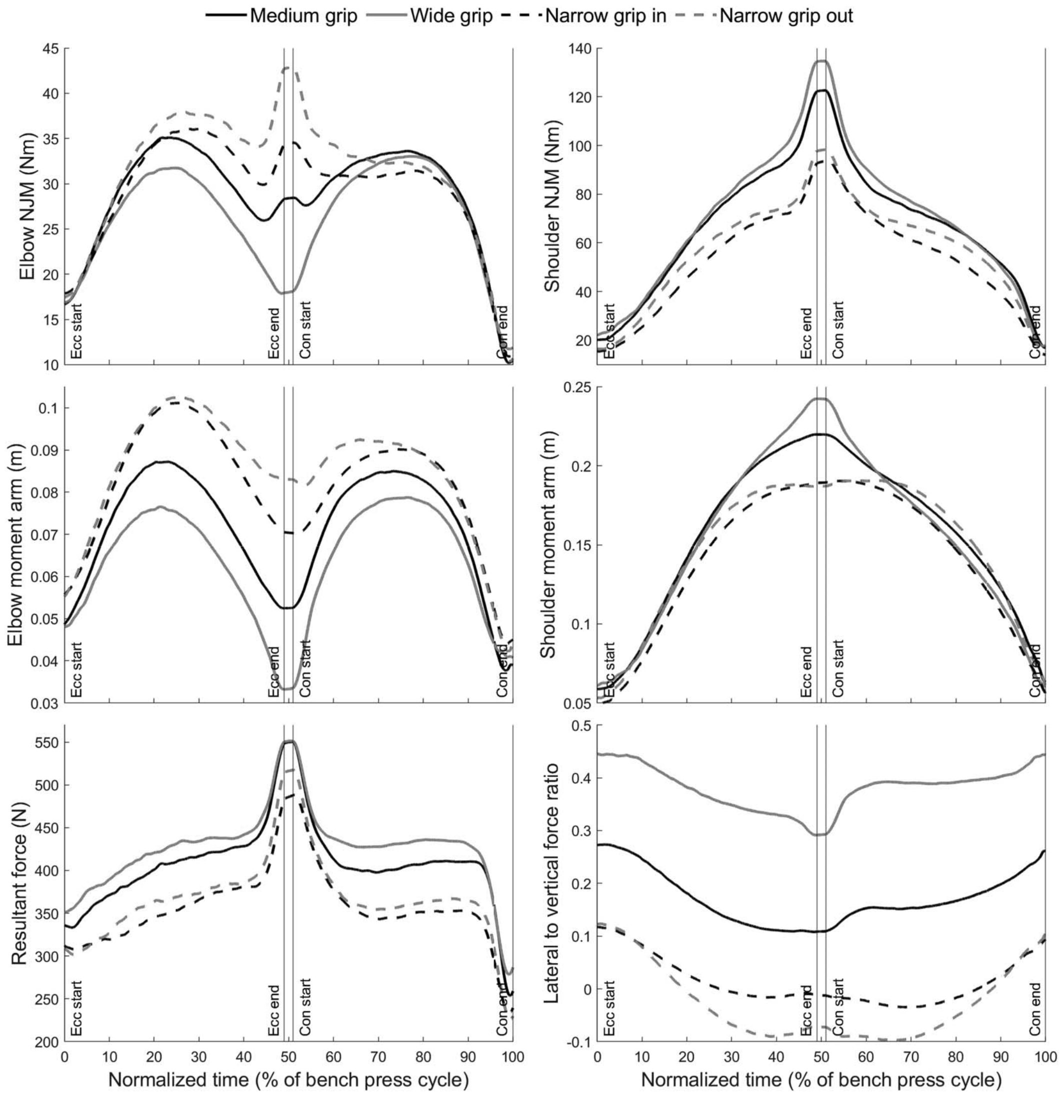

Figure 4. Net joint moments (top), moment arms (middle), and forces acting on the barbell (bottom) during the bench press with different grip widths and elbow positioning. Data are time normalized to the eccentric and concentric phases and displayed as ensemble average curves. Vertical lines represent the start and end of the eccentric and concentric phases. NJM = net joint moment; elbow NJM = external elbow flexion NJM; shoulder NJM = external shoulder extension/horizontal abduction NJM.

the eccentric and concentric phases, and shoulder moment arms close to the bottom position of the lift (Figure 4).

There were significant main effects for bench press type for mean resultant force ($p < 0.001$, $\eta_p^2 = 0.68$) and mean lateral to vertical force ratio ($p < 0.001$, $\eta_p^2 = 0.97$) (Table 2). Peak resultant forces and peak lateral to vertical force ratios occurred at the bottom and top position of the lift, respectively (Figure 4).

Mean elbow nNJMs were similar among bench press conditions ($p = 0.224$, $\eta_p^2 = 0.04$), yet peak elbow nNJMs ($p = 0.001$, $\eta_p^2 = 0.20$), and mean ($p < 0.001$, $\eta_p^2 = 0.33$) and peak ($p < 0.001$, $\eta_p^2 = 0.65$) shoulder nNJMs were significantly different (Table 2).

Muscle Activity

EMG activity of the triceps brachii was significantly different across bench press variations for the mean ($p = 0.001$, $\eta_p^2 = 0.18$) and peak ($p < 0.001$, $\eta_p^2 = 0.24$) activity of the lateral head, but not for the mean and peak activity of the long head ($p \geq 0.058$, $\eta_p^2 = 0.02$–0.08) (Table 3). A significant main effect was found for mean ($p = 0.011$, $\eta_p^2 = 0.13$) and peak ($p < 0.001$, $\eta_p^2 = 0.28$) activity of the anterior deltoid (Table 3). For the pectoralis major, main effects for bench press type were significant for the clavicular head (mean: $p < 0.001$, $\eta_p^2 = 0.29$; peak: $p < 0.001$, $\eta_p^2 = 0.23$) and the abdominal head (mean: $p < 0.001$, $\eta_p^2 = 0.25$; peak: $p < 0.001$, $\eta_p^2 = 0.22$), yet not for the sternocostal head ($p \geq 0.412$, $\eta_p^2 = 0.02$–0.03) (Table 3). A difference in mean and peak activity of the biceps brachii was observed among bench press conditions ($p < 0.001$, $\eta_p^2 = 0.39$–0.42) (Table 3). All muscles, apart from the biceps brachii (not presented because of low activity), reached greater EMG activity during the concentric than the eccentric phase for all bench press variations (Figure 5).

Kinematics

Bench press type affected peak elbow flexion angle and elbow flexion ROM ($p < 0.001$, $\eta_p^2 = 0.93$–0.95), with significant differences occurring among all exercise variations. The peak elbow flexion angle and ROM were largest for BPNO (114.1 ± 7.6° and 88.4 ±

Table 3
Mean and peak electromyographic activity during performance of the bench press with different grip widths and elbow positioning.*†

	Medium	Wide	Narrow in	Narrow out
Triceps, lateral head, mean (% MVIC)	74.5 ± 18.6§	69.1 ± 17.0‡‖¶	76.0 ± 18.3§	77.9 ± 20.7§
Triceps, lateral head, peak (% MVIC)	128.1 ± 36.0§	114.4 ± 29.0‡‖¶	131.7 ± 33.6§	131.8 ± 37.3§
Triceps, long head, mean (% MVIC)	59.8 ± 17.5	57.2 ± 18.5	58.6 ± 16.0	61.1 ± 18.4
Triceps, long head, peak (% MVIC)	108.2 ± 26.9	104.9 ± 28.0	105.7 ± 25.4	107.2 ± 30.9
Anterior deltoid, mean (% MVIC)	59.0 ± 19.3§	52.4 ± 17.4‡	61.4 ± 26.2	58.0 ± 23.1
Anterior deltoid, peak (% MVIC)	112.6 ± 33.2§	97.3 ± 30.8‡‖¶	126.3 ± 48.2§	118.5 ± 43.9§
Pectoralis, clavicular head, mean (% MVIC)	56.0 ± 17.5§‖	52.4 ± 14.6‡‖¶	59.6 ± 17.0‡§	56.3 ± 15.7§
Pectoralis, clavicular head, peak (% MVIC)	99.4 ± 28.3§	93.3 ± 24.8‡‖¶	105.1 ± 25.5§	102.9 ± 28.4§
Pectoralis, sternocostal head, mean (% MVIC)	52.1 ± 15.0	51.6 ± 15.9	51.5 ± 16.4	50.3 ± 14.4
Pectoralis, sternocostal head, peak (% MVIC)	101.6 ± 29.1	96.0 ± 27.5	98.8 ± 27.6	100.0 ± 26.4
Pectoralis, abdominal head, mean (% MVIC)	61.1 ± 24.8‖¶	64.9 ± 23.5‖¶	54.6 ± 24.7‡§	53.7 ± 22.2‡§
Pectoralis, abdominal head, peak (% MVIC)	112.4 ± 43.2‖¶	117.7 ± 43.7‖¶	99.7 ± 45.1‡§	101.4 ± 38.9‡§
Biceps, mean (% MVIC)	10.6 ± 5.6§‖¶	12.2 ± 5.9‡‖¶	9.1 ± 5.4‡§	9.4 ± 5.3‡§
Biceps, peak (% MVIC)	22.2 ± 11.3§‖¶	28.1 ± 14.7‡‖¶	16.3 ± 9.4‡§	16.3 ± 9.0‡§

*MVIC, maximum voluntary isokinetic contraction.
†Values are means ± *SD*.
‡Significant difference to medium grip width ($p \leq 0.05$).
§Significant difference to wide grip width ($p \leq 0.05$).
‖Significant difference to narrow grip width, elbows in ($p \leq 0.05$).
¶Significant difference to narrow grip width, elbows out ($p \leq 0.05$).

12.2°, respectively), followed by BPNI (110.3 ± 7.1° and 86.2 ± 11.5°, respectively), BPM (101.4 ± 8.3° and 78.3 ± 11.9°, respectively), and BPW (87.4 ± 8.1° and 64.7 ± 10.4°, respectively). Peak shoulder horizontal adduction angles and shoulder horizontal adduction ROMs ($p < 0.001$, $\eta_p^2 = 0.91$–0.97) differed significantly across all bench press conditions, with values decreasing from BPNI (65.2 ± 5.2° and 75.9 ± 10.6°, respectively) to BPNO (64.0 ± 5.1° and 70.2 ± 8.5°, respectively), BPM (56.1 ± 4.6° and 65.8 ± 8.9°, respectively), and BPW (47.0 ± 4.4° and 56.5 ± 8.6°, respectively). At the bottom position of the lift, shoulder horizontal adduction angles varied between −6.2° and −10.8°. The shoulder abduction angle at the bottom position of the lift ($p < 0.001$, $\eta_p^2 = 0.82$) was different between all bench press conditions apart from BPM compared with BPNO, with the largest angle present during BPW (66.1 ± 7.0°), followed by BPM (59.3 ± 8.2°), BPNO (56.5 ± 7.0°), and BPNI (37.9 ± 7.2°). The mean forearm angle ($p < 0.001$, $\eta_p^2 = 0.96$) differed among all exercise variations, decreasing from BPW (12.5 ± 3.9°), to BPM (−0.8 ± 4.7°), BPNI (−8.5 ± 3.3°), and BPNO (−16.5 ± 3.9°). The mean arching angle ($p < 0.001$, $\eta_p^2 = 0.58$) differed also among all exercise variations, with the largest angle occurring during BPW (32.3 ± 5.5°), followed by BPM (29.9 ± 6.5°), BPNO (28.0 ± 5.5°), and BPNI (25.8 ± 4.8°).

Discussion

This is the first study to include lateral barbell forces in the calculation of NJMs and to integrate measurements of both NJMs, nNJMs, and normalized EMG during execution of the bench press exercise. As expected, the lateral barbell forces increased substantially with grip width and had major implications for the moment arms and NJMs. All bench press variations achieved high elbow and shoulder muscular efforts. Changes in grip width and the accompanied changes in joint and segment kinematics significantly impacted joint kinetics and muscle activity during the bench press exercise. Specifically, a decrease in grip width induced larger elbow NJMs, as well as larger EMG activity of the lateral head of the triceps brachii, anterior deltoid and clavicular head of the pectoralis major. An increase in grip width was accompanied by larger shoulder NJMs and nNJMs, and larger EMG activity of the abdominal head of the pectoralis major.

Electromyography measurements are often used in isolation to describe the muscular efforts in the bench press exercise and its variations. However, the results of our study reveal considerable differences between EMG and NJM measurements, giving us different images of the loading profile in the bench press. For instance, there is a lack of concordance between the shoulder NJMs and pectoralis major activity at the bottom position of the lift, i.e., high NJMs yet relatively low muscle activity, and in the middle of the concentric phase, i.e., relatively low NJMs yet high muscle activity (Figures 4 and 5). The former discrepancy may be related to passive storage and release of elastic energy from the muscle-tendon unit of the pectoralis major during the transition from the eccentric to the concentric phase. Also, changes in muscle length and thickness during the bench press cycle may play a role, as previous research showed that larger muscle lengths caused increased NJM production, yet reduced muscle activity during maximal isometric contractions (40). Such divergences underline the importance of complementing EMG with NJM and nNJM measurements to improve our understanding of exercise biomechanics.

The magnitude of the muscular forces elicited by a resistance training exercise has a determining influence on strength and hypertrophy adaptations (13). In our study, muscular efforts, i.e., nNJMs and normalized EMG activity, were measured to estimate the relative forces produced by the elbow and shoulder muscles during the bench press and to make assumptions about potential strength training adaptations. Large peak elbow nNJMs (≥78% MVIC) and peak EMG activity of the triceps brachii (≥105% MVIC), as well as large peak shoulder nNJMs (≥112% MVIC) and peak EMG activity of the anterior deltoid and pectoralis major (≥93% MVIC) indicate that all bench press variations are likely to confer beneficial effects on strength and hypertrophy of the elbow extensors and shoulder flexors and horizontal adductors. As expected, low peak EMG activity of the biceps brachii (≤28% MVIC) and the presence of external elbow flexion NJMs imply that the bench press does not stimulate the biceps. Our results coincide with previous bench press research,

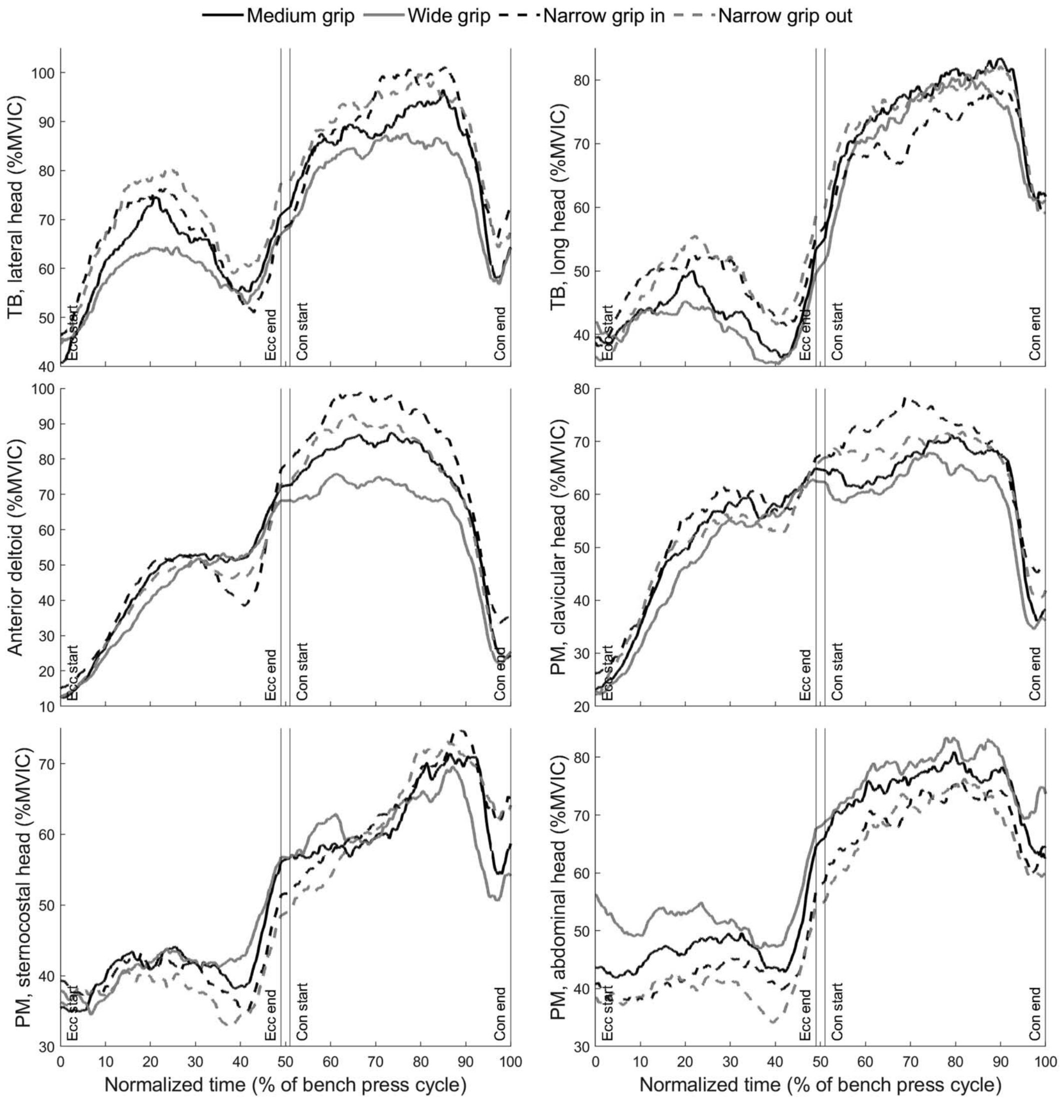

Figure 5. Electromyographic (EMG) activity of upper extremity muscles during the bench press with different grip widths and elbow positioning. Data are time normalized to the eccentric and concentric phases and displayed as ensemble average curves. Electromyographic activity is normalized to maximum voluntary isokinetic contractions (MVICs). Vertical lines represent the start and end of the eccentric and concentric phases. TB = triceps brachii; PM = pectoralis major.

revealing EMG activity of the triceps brachii above 80% MVIC and of the pectoralis major and anterior deltoid above 76% MVIC (32).

In terms of muscular loads, all bench press variations were clearly shoulder dominant, with shoulder NJMs on average 2.1 times greater than elbow NJMs (Table 2). That implies that the shoulder muscles were responsible for moving most of the load. This is plausible, as 1.8–1.9 times larger NJMs could be generated during the shoulder horizontal adduction than during the elbow extension MVIC. However, in terms of muscular efforts, elbow extensors and shoulder horizontal adductors were more similarly loaded, with shoulder nNJMs on average 1.2 times larger than elbow nNJMs (Table 2), and normalized EMG activity of the elbow extensors on average 1.3 times larger than EMG activity of the shoulder muscles (Table 3). We can therefore assume that the bench press is similar effective for training the elbow and shoulder muscles.

Force measurements are the basis for NJM calculations and are therefore crucial for the proper understanding of exercise biomechanics. This is the first study to measure the lateral forces acting on the barbell during the bench press and to include these in the calculation of NJMs. We found a considerable increase of the lateral to vertical force ratio with grip width (Table 2). By contrast, and against expectation of the author, Duffey (9) found a slight decrease of the lateral to vertical force ratio as grip width increased. This finding is surprising as it contradicts basic mechanical principles. Irrespective of grip width, his observed force ratio remained between 0.25 and 0.30 and was therefore larger than the ratio reported in our study for the medium grip width (0.17), yet lower than the ratio for the wide grip width (0.38).

In line with previous research (29,37), wide and medium grip widths permitted up to 12% more load to be lifted than narrow grip widths. Therefore, individuals aiming at enhancing their bench press performance should apply wider grip widths. Several factors may explain this difference in RM load. First, 14–26% larger NJMs can be produced during a shoulder horizontal adduction, the predominant shoulder movement during wider grip bench presses, as compared with a shoulder flexion (20), which prevails during narrow grip widths. Second, subjects displayed greater arching angles with increasing grip widths, thereby reducing the vertical displacement at the bottom position of the lift, where shoulder moment arms and NJMs were largest. Third, wider grip widths permitted larger shoulder NJMs and nNJMs to be generated and allowed for greater muscle activity of the abdominal head of the pectoralis major, indicating that a larger muscle mass was involved.

As expected, and in agreement with previous research (9,14,29), a decrease in grip width induced larger peak elbow flexion angles and ROM, larger shoulder horizontal adduction ROM, smaller forearm angles, as well as smaller shoulder abduction angles at the bottom position of the lift. As performing resistance training through a larger ROM has been shown to confer beneficial effects on muscle growth (30), narrower grip widths may yield greater hypertrophic adaptations. However, this is probably only applicable to the elbow extensors, as narrow grip widths caused the elbow flexion ROM to increase toward the bottom position of the lift, where high elbow NJMs were present. Contrarily, narrow grip widths caused the shoulder horizontal adduction ROM to increase only toward the top position of the lift, where shoulder NJMs were relatively low.

Most previous studies used biacromial distance (BAD) to standardize grip widths and commonly applied 100% BAD, 150% BAD, and 200% BAD to the narrow, medium, and wide grip width, respectively (1,4,9). We assumed that applying the same arm-barbell angle across subjects with various anthropometrics would provide more homogenous upper-body kinematics and lifting techniques than applying the same BAD. Compared with previous studies, our grip widths were slightly wider for the narrow (112 ± 4% BAD), medium (163 ± 5% BAD), and wide (210 ± 8% BAD) grip widths.

Larger effect sizes for the shoulder NJMs and nNJMs (η_p^2 = 0.33–0.78) than for the elbow NJMs and nNJMs (η_p^2 = 0.04–0.50) indicate that the effect of grip width was more pronounced on the shoulder muscular loads and efforts than on the elbow muscular loads and efforts. Therefore, modifications of grip width may influence strength and hypertrophy adaptations of the shoulder muscles to a greater extent than of the elbow muscles.

As grip width decreased, mean and peak elbow NJMs increased by up to 26% (Table 2). This difference in elbow NJMs across grip widths (η_p^2 = 0.32–0.50) was prompted by an even larger difference in elbow moment arms (η_p^2 = 0.72–0.73), yet attenuated by the heavier loads being lifted with wider grip widths, resulting in larger resultant forces. Not only grip width but also elbow positioning during the narrow grip width affected mean and peak elbow NJMs. In the absence of differences in elbow moment arms between BPNO and BPNI, the 7–11% larger elbow NJMs elicited when keeping the elbows away from the body can be related to a larger force production during BPNO. It should be noted that the elbow NJMs at the bottom position of the lift differed substantially across grip widths, with up to 140% larger NJMs during narrow grip bench presses (Figure 4). As strength gains are generally joint angle specific (19), greater strength adaptations of the elbow extensors may be expected at larger elbow flexion angles, i.e., around 110°, when using narrow grip widths, especially if the elbows are kept away from the body. For the medium and wide grip widths, elbow NJMs peaked at around 70–80° elbow flexion, indicating that the largest strength gains may occur near this range. In accordance with the peak elbow NJM, the peak elbow nNJM was up to 14% larger for BPNO than for all other conditions (Table 2).

We found up to 15% larger EMG activity of the lateral head of the triceps brachii for the narrow and medium grip widths compared with the wide grip width (Table 3). This coincides with results from Lehman (21), who even found larger activity during the narrow grip width compared with the medium grip width, but contradicts Duffey (9) revealing no differences across bench press conditions. The absence of differences in EMG activity of the long triceps head in our study could be related to its different muscle function as compared with the lateral head, although Barnett et al. (1) found a difference in long head activity in favor of a narrow grip width. In concordance with Saeterbakken et al. (29), biceps brachii activity increased with grip width, yet Lehman (21) and Duffey (9) found no differences. Conflicting EMG results may be related to different methodological approaches, such as differences in grip width, loading, training experience, processing of the EMG signal, or whether the same absolute or relative load was applied. The well-known limitations of EMG measurements, such as neighboring crosstalk and noise sensitivity (8), may also play their part. The increasing elbow NJM with decreasing grip widths can explain the overall tendency toward larger triceps activity with narrower grip widths, with most of the NJM increase appearing to be distributed on the lateral triceps head.

The combined results of the NJMs, nNJMs, and EMG activity, in addition to results of previous EMG studies, indicate that narrower grip widths, especially BPNO, induce larger elbow muscular loads and efforts through a greater ROM. However, less distinct differences in nNJMs and EMG activity with relatively low effect sizes, as well as partly contradicting results from previous EMG studies, indicate that the magnitude of the difference in the elbow muscular effort is relatively small. Eventually, slightly greater strength and hypertrophy adaptations of the triceps, possibly to a greater extent of the lateral head, may be expected when using narrower grip widths, especially when keeping the elbows away from the body. On the other side, narrower grip widths and particularly BPNO, will also elicit larger elbow joint loading, especially at greater elbow flexion angles. Therefore, individuals suffering from elbow pain or injury may be recommended to approach bench press training using wider grip widths initially.

Mean and peak shoulder NJMs increased by up to 43% (η_p^2 = 0.70–0.78) with grip width (Table 2). This increase can be attributed to increasing shoulder moment arms and increasing resultant forces caused by the heavier loads being lifted with wider grip widths. Shoulder NJMs were not only affected by grip width but also by elbow positioning during the narrow grip width. A larger mean shoulder moment arm, probably caused by the medial force component acting on the bar, as well as a greater resultant force production, resulted in a 9% larger mean shoulder NJM when keeping the elbows away from the body. During all bench press conditions, shoulder NJMs peaked at the bottom position of the lift, i.e., around −10° to −5° shoulder horizontal adduction (Figure 4), suggesting that the largest strength gains of the shoulder horizontal adductors and flexors may occur near this range. In accordance with the shoulder NJMs, mean and peak shoulder nNJMs generally increased with grip width (Table 2), with an increase by up to 34%.

EMG activity of the anterior deltoid and the clavicular head of the pectoralis major were up to 30 and 14% larger during the narrow and medium grip widths compared with the wide grip width, respectively (Table 3). Their similar behavior with decreasing grip widths can be explained by their common muscle function, i.e., shoulder flexion, which becomes the predominant shoulder movement as grip width decreases. Contrary to our

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findings, several previous studies (9,21,29) found no differences among grip widths in neither of these muscles, yet Barnett et al. (1) found the same result for the clavicular head. The lack of differences in these studies may be related to low statistical power because of few subjects. In agreement with previous research (1,29), we found no difference in EMG activity of the sternocostal head of the pectoralis major between bench press conditions. Lehman (21), however, found larger activity with wider grip widths. There is no previous research measuring EMG activity of the abdominal head of the pectoralis major during the bench press with different grip widths. In our study, an up to 21% increase in abdominal head activity with increasing grip width was found and can be attributed to the change in movement pattern from shoulder flexion with narrower grip widths toward shoulder horizontal adduction with wider grip widths, which is a major muscle function of the abdominal head. Furthermore, a greater arching angle during wider grip widths may yield a degree of shoulder adduction which also matches the function of the abdominal head. The absence of an increase in sternocostal head activity with grip width, despite having a similar function as the abdominal head, may be related to its close vicinity to the clavicular head, whose activity decreases with grip width.

The combined results of the NJMs, nNJMs, and EMG activity, in addition to results of previous EMG studies, indicate that wider grip widths induce larger shoulder muscular loads and efforts. This increase seems to be placed mainly on the abdominal head of the pectoralis major, whereas narrower grip widths place more load on the clavicular head and the anterior deltoid. Eventually, greater strength and hypertrophy adaptations of the abdominal head of the pectoralis major may be expected when using wider grip widths, whereas narrower grip widths may yield greater adaptations of the clavicular head and anterior deltoid. On the other side, wider grip widths will also elicit larger shoulder joint loading and reduce the subacromial space because of a greater degree of shoulder abduction (22). Therefore, individuals suffering from shoulder pain or injury may be recommended to approach bench press training using narrower grip widths initially.

The nNJMs measured in this study may overestimate the true percentage of the shoulder and elbow muscles' maximal strength which was required during the bench press because NJMs measured during single-joint dynamometry may underestimate the actual maximal strength of the muscle group (5) and may be lower than the NJMs which can be produced during multiple joint tasks (15).

Some limitations are related to the instrumented barbell used in this study. First, the vertical force could not be measured separately at each hand and was therefore assumed to be equally distributed among the right and left hand. Second, the location of the point of force application, i.e., the center of pressure, could not be measured. Data from pilot testing, where subjects performed push-ups with push-up bars on a force plate, were used to make best possible assumptions about its precise location. Third, the barbell diameter (52 mm) was larger than of a common Olympic bar (28 mm) and was therefore unfamiliar to the subjects. However, barbell thickness did not influence bench press performance in previous studies (26).

Furthermore, we used a moment arm approach to calculate simplified NJMs, thereby ignoring the inertia of the upper extremity segments. However, this approach has been proven to highly correlate ($r = 0.95$) with inverse dynamics calculations for the lower extremities during sidestep cutting (17). The correlation is probably even higher for the bench press, as upper extremity masses and segment accelerations are substantially lower.

Finally, long-term training studies must be conducted to confirm that the observed differences in the muscular loads and efforts between the bench press variations translate into different training adaptations in terms of hypertrophy and strength.

Practical Applications

Large elbow and shoulder muscular efforts indicate that all bench press variations can be used effectively to stimulate strength gains and hypertrophy of the elbow extensors and shoulder flexors and horizontal adductors. The effect of grip width was more pronounced on the shoulder muscular loads and efforts than on the elbow muscular loads and efforts and modifications of grip width may therefore influence strength training adaptations of the shoulder muscles to a greater extent than of the elbow muscles. An increase in grip width induced larger shoulder muscular loads and efforts and a decrease in grip width larger elbow muscular loads and efforts. Therefore, greater strength and hypertrophy adaptations of the shoulder horizontal adductors may be expected when selecting wider grip widths, whereas greater adaptations of the elbow extensors and shoulder flexors may be elicited by narrower grip widths. For targeting the elbow extensors even more, elbows should be kept away from the body. Greater joint loading contraindicates wide grip widths for individuals with shoulder pain and narrow grip widths for individuals suffering from elbow pain. Finally, the choice of grip position for the bench press should also be determined in light of sport specificity and functionality. Integrating measurements of NJMs, nNJMs, and normalized EMG enhances the understanding of exercise biomechanics and the inferences about potential strength training adaptations and should therefore be adopted more frequently in strength training research.

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