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Factors underlying bench press performance in elite competitive powerlifters

Running title: Determinants of bench press performance

ABSTRACT

Previous investigations of one-repetition maximum bench press (1 RM BP) performance have been either descriptive or have explored a limited number of contributing variables. The purpose of this study was to investigate the interplay between structural, technical and neuromuscular factors in relation to 1 RM BP in competitive powerlifters. Thirteen national and international level male powerlifters (26±9 years, 178±6 cm, 93.8±9.9 kg) visited the laboratory twice. Anthropometric and ultrasound measures were taken on the first visit, whereas performance measures (voluntary activation level, isokinetic strength, and kinetic, kinematic and electromyographic measurements during 1 RM BP) were recorded on the second visit. Correlation and multiple regression were used to investigate the contribution of structural, technical and neuromuscular variables to 1 RM BP corrected for body mass using the Wilks coefficient. The highest degree of association was shown for structural (lean and bone mass, brachial index, arm circumference and agonist cross-sectional area; $r = 0.58$–0.74) followed by neuromuscular factors (elbow and shoulder flexion strength; $r = 0.57$–0.71), whereas technical factors did not correlate with 1 RM BP performance ($r \leq 0.49$). The multiple regression showed that lean body mass, brachial index and isometric shoulder flexion torque predicted 59% of the common variance in 1 RM BP. These data suggest that in a sample of elite competitive powerlifters, multiple factors contribute to 1 RM BP with variables such as lean body mass, the agonist cross-sectional area, brachial index, and strength of the elbow and shoulder flexors being the greatest predictors of performance.

Key words: kinematics, kinetics, lean body mass, muscle architecture, neuromuscular, maximal strength, regression

INTRODUCTION

The bench press (BP) is a commonly prescribed exercise in resistance training programs and usually forms an integral part of strength and conditioning programs of various sports for the development of upper body strength and power (9,10,36). Furthermore, BP is part of the sport of powerlifting along with the squat and the deadlift. Thus, a better understanding of the factors that contribute to performance in 1 RM BP may be beneficial for many populations to improve training practice.

A variety of factors could contribute to 1 RM BP performance. A strong relationship between lean body mass and muscle mass and performance in 1 RM BP has been shown (5,21,43). It has been postulated that the expression of maximum strength in BP is somewhat limited by the capacity of skeletal muscle mass accumulation (5). Muscle architecture might also play a role in BP performance, with a strong positive and a moderate negative correlation shown between 1 RM BP and fascicle length and pennation angle, respectively (5).

Generally, the differences in body segments of individuals could have a large number of effects on kinematic and kinetic variables associated with BP performance. For example, humerus length could influence the elbow and shoulder angle at the sticking region, which is defined as a deceleration phase in the concentric portion of BP between the highest and the lowest bar speeds and occurs as a consequence of disadvantageous mechanical position in relation to the force-length relationship of a muscle (11,29,39). A study comparing successful and unsuccessful 1RM BP attempts found 8% lower elbow torque in sticking region in successful attempts (38). This could be explained by lower angles of elbow flexion and horizontal shoulder adduction at the lowest bar speed in successful attempts. Additionally, the height of the lumbar spine arch and force against the ground exerted by the feet may be an important contributor to successful BP in powerlifting according to the anecdotes from athletes and their coaches. To our knowledge there are not any available data on these two factors in the present literature.

Given it is well established that the gain in strength is related to the adaptations within the central nervous system (CNS) (7,34), the possible role of variations in CNS inputs to the muscle contributing to force application during BP exercise cannot be discounted. The muscle contributions to BP have been inferred from electromyographic (EMG) studies showing the greatest role of pectoralis major, triceps brachii, anterior deltoid and latissimus dorsi (26,39). Interestingly, muscle activity of the synergists in BP movement in the group of advanced lifters tend to exhibit greater variability compared to novice lifters, suggesting that more advanced lifters have more individualized motor strategies compared to novice lifters (24). Thus, athletes such as powerlifters may exhibit a unique pattern of muscle activity that allows them the greatest expression of strength. However, whilst the descriptive data on neural activity during BP performance exist, the direct contribution to 1 RM BP is less understood. Furthermore, the influence of the ability of CNS to activate the integral muscles in BP as measured by the interpolated twitch technique (32) remains unknown.

Previous investigations of 1 RM BP performance have been either descriptive (e.g. assessing biomechanics or muscle contributions) or have only studied a limited number of contributing variables (11,24,26,29,38,39). Considering a myriad of aforementioned factors that could influence 1 RM BP performance, the aim of this study was to investigate a number of possible determinants of the 1RM BP performance collectively among competitive powerlifters who are the athletes that likely exhibit the highest performance in this exercise. The determinant factors analyzed were grouped into three main categories: a) structural factors consisting of body composition and other anthropometric parameters, b) technical factors consisting of arm and bar kinematics, the height of the low back arch and the force against the ground exerted by the feet and c) neuromuscular factors consisting of voluntary activation level of the elbow extensors, EMG activity of pectoralis major, triceps brachii, anterior deltoid and latissimus dorsi in the concentric phase of 1 RM BP, the parameters of muscle architecture and the parameters of maximum isokinetic and isometric strength.

METHODS

Experimental approach to the problem

A cross-sectional study design was used to investigate the interplay between structural, technical and neuromuscular factors affecting 1 RM BP performance. Participants visited the laboratory on two separate occasions. During the first session, anthropometric and ultrasound measures were taken. On the second session, performance measures including voluntary activation, isokinetic strength, and kinetic, kinematic and EMG measurements during 1 RM BP were recorded (see Figure 1 for raw traces from a single participant). The two experimental visits were separated by 2 weeks. A pool of 36 dependent variables, including structural, neuromuscular and technical measures were analyzed. Correlation analysis and linear regression were applied to reveal which variables are associated with BP performance, with 1 RM BP as a criterion variable.

Figure 1 about here

Subjects

Thirteen male competitive powerlifters voluntarily participated in the study (mean ± standard deviation: 26 ± 9 years, range 18-26 years, plus one subject of 53 years of age; 178 ± 6 cm, 93.8 ± 9.9 kg). All participants were national and international level competitors in powerlifting under the rules governed by the International Powerlifting Federation (Table 1) and had achieved a 1 RM BP in competition corresponding to at least 90 Wilks points (40) in the last year. All participants were informed of the risks and benefits of the study and signed informed consent prior to taking part. The procedures of the study were approved by the Slovenian National Medical Ethics Committee and were carried out in accordance with Declaration of Helsinki.

* Table 1 about here*

Procedures

Anthropometric variables

Anthropometric measures (Siber-Hegner & co., GPM, Switzerland) including stature, segment lengths (upper arm, forearm, hand), widths (shoulders, hips), chest depth, arm span and circumferences (forearm, relaxed and flexed upper arm, chest, stomach, hips, thighs, shanks) as well as skinfolds (forearm, biceps, chest, supraspinal, anterior thigh, posterior shank) were performed according to International Society for the Advancement of Kinanthropometry guidelines. All measures were taken twice on the right side of the subject's body. If the two measures differed by more than 5%, another measure was taken and the median was considered as a representative value. Otherwise, the mean of the two measures was calculated. Matiegka's fat mass equation (30) was used for lean body mass extrapolation. Brugchs (chest circumference/height), brachial (forearm/upper arm length) and ilio-acromial (iliac/acromial width) index (20) and arm length to body height ratio were also calculated. Body, fat, lean body and bone mass data were also acquired with a bioimpedance scale (Tanita MC-980MA, Tanita, Tokyo, Japan). In the 2h period prior to the bioimpedance scale measurements, participants were instructed not to consume any food or liquids.

Ultrasonography

Ultrasound measures (Noblus, Hitachi, Wallingford, USA) of the muscle cross-sectional area (CSA) were obtained on the right side of the body at 9 posterior and anterior sites. Location of the sites and the extrapolation of lean body mass were performed as per Abe et al. (2). Additionally, CSA of pectoralis major and anterior deltoid was also acquired. Ultrasound measures were done by an experienced radiologist. The ultrasound probe (C251, 5 – 1MHz for CSA of quadriceps and hamstrings; L55, 13 – 5 HHz for everything else) was held perpendicular to the measuring spot without compressing the tissue. CSA was defined as the distance between the fat and the bone tissue (Figure 2A). Muscle architecture was also measured with the ultrasound device. The probe was held perpendicular to the measuring spot at the 40% of the proximal distance of triceps brachii in parallel to the pennation angle of the muscle. The angle between muscle aponeurosis and muscle fascicles was defined as pennation angle (Figure 2B). Muscle fascicle length was defined as a ratio of CSA and the sine function of the pennation angle (5).

Figure 2 about here

Voluntary activation

Voluntary activation of the elbow extensors was measured with interpolated twitch technique (rectangular, bi-phasic, energy balanced single pulse, 1 ms width; EMF Furlan & Co d. o. o., Ljubljana, Slovenia). Two self-adhesive stimulating electrodes (5 × 5 cm; Marc Pro, California, USA) were placed on the belly of triceps brachii ensuring minimal antagonist coactivation. Initially, the intensity of the stimulation that elicited a plateau in single twitch torque at rest was noted and then further increased by 50 % to ensure a supramaximal stimulation impulse. After a 5-minute rest, stimulation was performed during a maximal voluntary contraction (MVC) plateau (superimposed twitch) and 5 s after MVC at rest (potentiated twitch). The procedure was repeated three times. During MVC performed to assess voluntary activation subjects seated upright and leaned against the wall with 40° shoulder flexion and 90° elbow flexion. Elbow was fixed on the surface with adjustable non-compliant belt. Voluntary activation was calculated as VA (%) = [1 – (superimposed twitch / potentiated twitch)] x 100 (32). Elbow flexion MVC was expressed both in absolute units (N) and relative to body mass of the individual. Since measures of muscle force (N) are expected to be proportional to the cross-sectional area of the muscle, and hence to the square of all body linear dimensions, the relative values were normalised to body mass to the power of 2/3 (17).

One repetition maximum

Before 1RM BP measurements subject underwent a standardized warm up with 20 repetitions at 20 kg followed by 2 sets of 6 repetitions at 40 % 1RM, 1 set of 3 repetitions at 60% 1RM, 1 set of 2 repetitions at 75% and 1 set of 1 repetition at 85% 1RM. The submaximal loads in the warm-up were based on the subjects' most recent result in the competition. 1RM loads were chosen individually by the subjects in the interest of ecological validity. Five minutes of rest was given after the last warm up set. During measurements 1RM loads could be increased, decreased or repeated with each attempt separated by at least 5 minutes and repeated for a maximum of 3 times. The greatest 1RM loads that was successfully and correctly (i.e. performed according to the rules of the International Powerlifting Federation) lifted were chosen for subsequent analysis. The Wilks coefficient was employed to standardize the weight lifted relative to the individual's body mass (40).

Kinematic and kinetic variables

Unilateral and bilateral forces of the feet to the ground during 1RM BP were measured with 2 force plates (Kistler force plate 9260AA, Kistler Group, Winthertur, Switzerland). Kinematic measurements were obtained with two 3D cameras (Optotrak Certus, NDI, Waterloo, Ontario, Canada) which tracked the position of the markers in x, y and z axes with frequency of 100 Hz. Markers were positioned on the barbell, and lateral acromion, lateral epicondyle and ulnar styloid bilaterally. Markers defined vertical and horizontal displacement of the barbell, shoulder flexion (flexion of the shoulder in the sagittal plane), horizontal shoulder flexion (flexion of the shoulder in the frontal plane), shoulder abduction and elbow extension angles observed at the point of the lowest speed of the barbell. The angles were calculated by transformation of two points from the three-dimensional space to each separate dimension, with each dimension representing flexion, abduction and horizontal flexion of the shoulder. The average of left and right arm for every subject separately was calculated. Based on kinematics of vertical bar displacement, distinct phases could be identified during the BP lift: onset of descent (eccentric portion), end of descent (eccentric portion), onset of ascent (concentric), onset of the sticking region (the point of maximal bar velocity during ascent), end of the sticking region (the point of minimal bar velocity during ascent) and end of ascent. Since the ability to overcome the sticking region is likely to be the main technical factor determining performance in 1 RM BP (22,23), the kinematic and kinetic factors were analyzed during the point of minimal bar velocity during the ascent. The height of the lumbar spine arch was measured with a constant force spring-based position sensor (Hottinger Baldwin Messtechnik, Darmstadt, Germany). The sensor was positioned right above the participant's trunk. A rigid light aluminium stick on the lumbar spine at the height of crista iliaca was fixed with elastic bands and connected to distance meter with a rigid thread. Maximum shift of the aluminium stick during concentric 1RM BP represented the height of the lumbar spine arch. Measurements of the kinematics were synchronized with EMG measurements.

Electromyography

Surface EMG was measured using a bipolar wireless surface EMG system (Trigno, Delsys, Massachusetts, USA). Electrodes were placed bilaterally on the muscle belly of the long head of triceps brachii, anterior deltoid, pectoralis major and latissimus dorsi as per SENIAM recommendations (16). Prior to electrode placement, the skin was shaved, abraded and cleaned with alcohol. Before sticking the electrodes to the skin, the contact rods (inter-electrode distance 20 mm) were greased with conductive paste Ten20 (Weaver & Company, USA) to ensure optimal conductance. For the purpose of normalization of the EMG signal, EMG recordings were performed during an MVC of a supine isometric press on the bench with 90° elbow flexion for pectoralis major, triceps brachii and anterior deltoid and during an MVC of a supine isometric pull in the same position for latissimus dorsi. Both pushing and pulling isometric MVCs were repeated 3 times. The mean EMG activity of the left and right muscle during the concentric part of the BP was calculated and normalized for every participant. The EMG signals were filtered (Butterworth band-pass, 3 to 500 Hz, level 2, zero phase shift) and smoothed (moving window root-mean-square, 20-ms window), followed by a linear envelope calculation (Butterworth 10 Hz low-pass filter, level 2, zero phase shift).

Maximal isokinetic strength

Maximal isokinetic strength was measured with an isokinetic dynamometer (CSMI Humac Norm, Stoughton, Massachusetts, USA). Subjects were positioned as per manufacturer's guidelines. Maximum concentric and eccentric torque of the shoulder flexion, elbow extension and horizontal shoulder flexion bilaterally was taken during 3 repetitions at maximum effort at 60°/s. The sum torque value for the left and the right limb was calculated. Maximal isokinetic strength variables were expressed both in absolute and relative units. For the latter it is important to note that rotational forces change with body size due to both cross-sectional area (body mass to the power of 2/3) as well as the change in the lever arm (body mass to the power of 1/3) of the muscle (17). Hence, the allometric parameter of 1 was used to express maximal isokinetic strength variables relative to the body size of the individual.

Statistical analyses

Data is presented as mean and 95% confidence interval (CI) limits, unless stated otherwise. All statistical analyses were performed using SPSS (v22, IBM, New York, ZDA). The level of statistical significance was set at an alpha level of 0.05. Normality of the data was assessed using Shapiro-Wilks test. Pearson's (r) and Spearman's (ρ), in the case of normal or non-parametric data distribution, respectively, were used to investigate correlations between dependent and independent variables and correlations within and between groups of variables. Correlations of < 0.3, $0.3 – 0.5$ and ≥ 0.5 were considered small, moderate and strong, respectively (8). Statistical power ($1–\beta$) was calculated using G*Power 3.1 (Heinrich-Heine University of Düsseldorf, Germany). Multiple regression was performed using independent variables with normal data distribution, strong ($r > 0.5$) and statistically significant correlation ($p < 0.05$) with dependent variable, and independent variables with acceptable level of multicollinearity ($r < 0.7$).

RESULTS

Average 1RM BP was 151.54 ± 21.00 kg and 95.26 ± 10.63 Wilks points, respectively. Since participants were of different weight categories, the result in the Wilks points was considered as the dependent variable.

In the group of structural factors, measures of lean body mass, CSA of agonists, bone mass and upper arm circumference exhibited positive and strong correlation with 1 RM BP performance ($r = 0.58 – 0.74$; Table 2). On the other hand, there was no statistical correlation between technical factors and 1 RM BP (Table 3).

Table 2 about here

Table 3 about here

Of the neuromuscular factors, elbow extension MVC, isokinetic concentric and eccentric shoulder flexion as well as concentric horizontal shoulder flexion positively and strongly correlated with 1 RM BP performance (r =

0.57 – 0.71; Table 4). However, when these variables were normalized to body mass, only isokinetic concentric shoulder flexion maintained strong and significant correlation (r = 0.64).

Table 4 about here

A multiple regression was run to predict 1RM BP from variables that showed strong and significant correlations with 1 RM BP – lean body mass (ultrasound), brachial index and isokinetic concentric shoulder flexion torque. The multiple regression model statistically significantly predicted 1RM BP (R = 0.83, R^2 = 0.69, adjusted R^2 = 0.59, p = 0.012). Regression coefficients and standard errors can be found in Table 5.

Table 5 about here

DISCUSSION

The purpose of this study was to investigate the determinants of 1 RM BP in competitive powerlifters. The highest degree of association with 1 RM BP was shown for structural followed by neuromuscular factors, whereas technical factors were not found to be associated with 1 RM BP performance. The multiple regression, which included only factors with strong and significant correlations with 1 RM BP showed that lean body mass, brachial index and isokinetic concentric shoulder flexion torque accounted for 59% of the common variances in 1 RM BP.

The findings from both multiple regression and bivariate associations showed that lean body mass is a high predictor of success in 1 RM BP, which corroborates previous investigations (5,28,43). Although lean body mass consists of skeletal muscle mass, bone mass and other organ tissues, it is still considered a good proxy of muscle size (1,5). Furthermore, the importance of lean body mass for successful 1 RM BP is also supported by strong correlations between upper arm circumferences and the sum of CSAs of prime movers to 1 RM BP. The results of the present study also showed strong correlations between bone mass and 1 RM BP. Higher levels of bone mass have been purported to be desirable for powerlifters due to more effective muscle mass accumulation (31) and more successful protection against compressive and shear force stemming from lifting maximal loads (12). Taken together, these results might not be considered surprising as muscle mass and muscle CSA have previously been shown to be associated with maximal strength (5,28,43). However, it was surprising to find that muscle mass seems to play a role in 1 RM BP performance even when related to the weight lifted corrected for body mass via the Wilks coefficient. Thus, it would appear that the better performers of 1 RM BP had accumulated more muscle mass within their weight class limit. Alternatively, even though the Wilks coefficient has been validated previously (40), it might be insufficiently sensitive to correct for body mass differences across athletes of different weight classes.

It has been suggested previously that skeletal dimensions might play a role in 1 RM BP, such that individuals with longer body segments would exhibit greater moment arms compared to smaller moment arms in individuals with shorter body segments (14,18). In the present study, only the brachial index was strongly associated with 1 RM BP. Whilst some previous studies have not observed differences in body segment length between more and less successful powerlifters (21), the present study supports the findings of a negative correlation between humerus length and BP performance in strength trained individuals (15). A greater brachial index could thus benefit mechanical efficacy of the movement by reducing the moment arm of the load and might be a factor in talent identification for powerlifters.

Despite a significant contribution of brachial index to 1 RM BP and our hypothesis that this could manifest itself in different kinematic profiles of more successful athletes, only weak or moderate correlations between technical factors and 1 RM BP were found. These findings are unexpected since a previous report has shown greater shoulder abduction in early concentric phase of the lift in elite level powerlifters (11). However, our analysis performed during the sticking region suggests only small contribution of kinematic factors to 1 RM BP performance. It is possible that athletes' performance in the laboratory could have been impeded by the experimental setup consisting of markers, electrodes and cables placed on or around subjects' body. However, it is also plausible that our findings indicate existence of individual technical strategies of bench pressing among competitive powerlifters, which might not be directly related to 'optimal' biomechanical profiles shown previously in the literature. This is also evident in the lack of significant contribution of the height of the lumbar spine arch and the forces to the ground exerted by the feet to 1 RM BP performance. It might be that those two variables are already maximized in this specific population and it remains contentious whether a comparison of a general strength-trained population in the study would have revealed the importance of the two factors.

Regarding neuromuscular factors, all athletes in the present study had maximal or near maximal voluntary activation of triceps brachii (98.3 ± 1.8%), which is reflective of neural adaptations as a result of heavy resistance training (34). Thus, it is not surprising that minimal between-subject variability in voluntary activation was not significantly associated with 1 RM BP performance. It is unclear whether the ability of the nervous system to maximally activate the agonist muscles is a contributing factor to 1 RM BP in untrained and less trained individuals compared to competitive powerlifters. Similarly to voluntary activation, EMG activity of muscle groups involved in the BP exercise was not found to be a significant contributing factor to its performance. The EMG activity of all muscles recorded peaked during the concentric phase of the lift, with the biggest activity shown for triceps brachii (160% of maximal EMG), followed by anterior deltoid (146%) and pectoralis major (129%) with a much smaller activity recorded in latissimus dorsi (52%; see Figure 2 for example response). The EMG activity was normalized to a maximal EMG recorded during a supine isometric press or pull with the elbow flexed at 90°. Whilst EMG activity in this position is likely confounded by co-contraction of other muscles, this strategy of normalization was chosen as it presented the most specific position during which stability requirements would likely be smaller than during a dynamic movement. However, the present data show that the activity of the pressing muscles during BP exceeds the one achieved during an isometric supine press where stability requirements would presumably be lower. This might reflect the specificity of adaptation in powerlifters, such that they are more efficient in performing dynamic supine press compared to an isometric equivalent. Alternatively, this might be the result of differences in maximal force producing capacity at different joint angles and differences in the corresponding muscle activity during BP (39). The findings that the activity of triceps brachii and anterior deltoid was the greatest are similar to those reported previously (25), but our data questions the importance of latissimus dorsi activity during BP (4,6,33). The differences in these results may be confounded by limitations of surface EMG recordings insofar as multi-joint muscles such as latissimus dorsi have multiple innervation zones (35) and the recorded activity will be thus highly dependent on the electrode placement. These limitations notwithstanding, it might be that the nonsignificant contribution of EMG activity to 1 RM BP performance along with relatively high between-subject variability (Table 3) represents the existence of individual strategies of muscle activity during BP in powerlifters as postulated previously (24).

Despite the complexity of BP as a multi-joint exercise including the involvement of trunk and leg musculature, the isolated, single-joint, isometric elbow extension and isokinetic concentric shoulder flexion and horizontal shoulder adduction as well as eccentric shoulder flexion significantly correlated with 1 RM BP. Whilst it seems that the strength of elbow extensors, shoulder flexors and horizontal shoulder adductors is an important factor for BP performance, the complexity of the BP exercise does not allow extrapolation as to which, if any, of those prime movers are the limiting factors to performance in the exercise. This is particularly the case as the isolated maximal actions of joints in a controlled environment with minimized synergistic and antagonist muscle contribution might not necessarily correspond to the demands during the BP exercise. It is, however, likely, that training programs should involve strengthening of those muscles to complement the specific training of the BP exercise. However, it should be noted that the association of these variables with 1 RM BP was largely absent when they were normalized to differences in body size. As such, not just strengthening, but also the accumulation of muscle mass of the relevant musculature involved in the BP exercise should be the goal of training to improve 1 RM BP performance. Conversely, muscle architecture variables were only moderately, but not significantly correlated with 1 RM BP performance. Compared to Brechue & Abe (5), our results showed similar correlations to 1 RM BP for pennation angle of triceps brachii (r = –0.46 vs. r = –0.45), but smaller correlation for muscle fascicle length (r = 0.27 vs. r = 0.52) with smaller pennation angles (14.7° vs. 28.1°–32.6°) and longer fascicles (81.7 mm vs. 61–78 mm). The accumulation of muscle mass may increase pennation angles which can negatively affect manifestation of maximum strength per CSA and therefore impede PL performance (5). However, this potential negative effect was likely mitigated by smaller pennation angles in conjunction with increased fascicle length (19,27) in the present study.

According to our regression model, 59% of the common variance in BP performance can be ascribed to lean body mass, the brachial index and isokinetic concentric shoulder flexion torque. This might suggest that other variables that were shown to be significantly correlated with 1 RM BP do not meaningfully contribute to its performance. However, this supposition should be interpreted with caution as individual variables might be correlated redundantly or their magnitude of influence is insufficient to be contributory to the regression model (41). It is unclear whether at least part of the unexplained regression model could be related to psychological factors that were not explored in the present experiment. For example, the phenomenon of self-efficacy (3) has been shown to play a significant role in expression of strength (13,37,42) and future investigations should explore its role in BP and other exercise in elite powerlifters. Lastly, it is unclear to what extent was performance confounded by fatigue due to repeated lifting of near-maximal loads.

In conclusion, the examination of the contribution of structural, technical and neuromuscular factors to 1 RM BP in elite powerlifters revealed that structural (lean body mass, cross-sectional area of agonists, bone mass, brachial index and upper arm circumference) and neuromuscular factors (elbow and shoulder flexion strength and pennation angle) are the greatest predictors of performance in the exercise. Furthermore, the regression model employed accounted for 59% of the common variance in 1 RM BP performance. These findings reiterate the importance of maximizing muscle mass with concomitant increases in strength for better performance outcomes in the sport of powerlifting. This is likely the case even within one’s weight category as lean body mass was shown to contribute to 1 RM BP when differences in body mass among the athletes were account for.

PRACTICAL APPLICATION

This study suggested that structural and neuromuscular factors need to be considered in predicting and possibly improving BP performance, while small variations in the exercise technique seem to play little or no role. Lean body mass, brachial index and isokinetic concentric shoulder flexion torque were particularly strong predictors of 1 RM BP. Muscle mass seems to play a role in BP performance, even when the results are corrected for body mass via the Wilks coefficient. Therefore, a training program designed to improve the 1 RM BP strength might also need to consist of additional exercises that facilitate muscle mass accumulation with an increase in strength. Among the skeletal dimensions, only the brachial index was strongly associated with 1 RM BP. Our findings support the notion that humeral length is inversely related to BP performance, which might be an important factor in selection and talent identification for the sport of powerlifting. Furthermore, moderate to strong association between 1 RM BP and several upper limb strength measures were shown, however, it is not possible to conclude which of those variables in particular are the most important. The conclusions from this study could support training practice in the sport of powerlifting, whilst the researchers can use these cross-sectional data for the formation of hypotheses for longitudinal training research.

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Figure captions

Figure 1. Example of quantification of kinetic, kinematic and EMG traces from a single participant during one-repetition maximum bench press performance. The vertical dashed lines denote the different phases of the bench press. The EMG activity was normalized to a maximal EMG recorded during a supine isometric press or pull MVC with the elbow flexed at 90°.

Figure 2. Example of an ultrasound image for muscle structure quantification. Muscle cross-sectional area (D1) was defined as the distance between the fat (D2) and the bone tissue (A), whereas the pennation angle (α) was calculated as the angle between muscle aponeurosis and muscle fascicles (B). Muscle fascicle length was then calculated as the ratio of cross-sectional area and the sine function of the pennation angle.

Figure 1

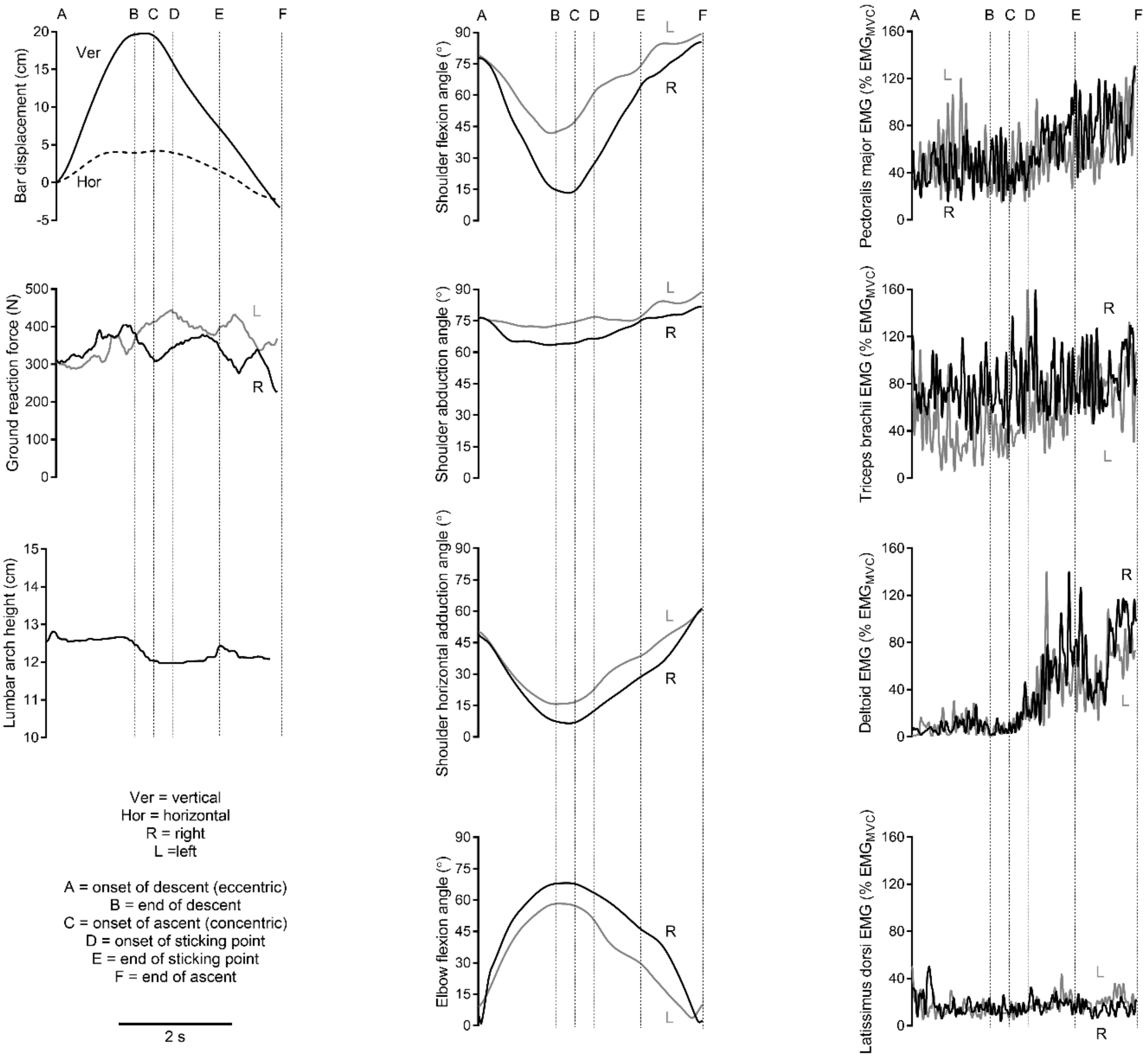
A B C D E F
Bar displacement (cm)
Ver
Hor
Ground reaction force (N)
Lumbar arch height (cm)
Shoulder flexion angle (°)
Shoulder abduction angle (°)
Shoulder horizontal adduction angle (°)
Elbow flexion angle (°)
Pectoralis major EMG (% EMG$_{MVC}$)
Triceps brachii EMG (% EMG$_{MVC}$)
Deltoid EMG (% EMG$_{MVC}$)
Latissimus dorsi EMG (% EMG$_{MVC}$)
R
L
Ver = vertical
Hor = horizontal
R = right
L =left
A = onset of descent (eccentric)
B = end of descent
C = onset of ascent (concentric)
D = onset of sticking point
E = end of sticking point
F = end of ascent
2 s

Figure 2

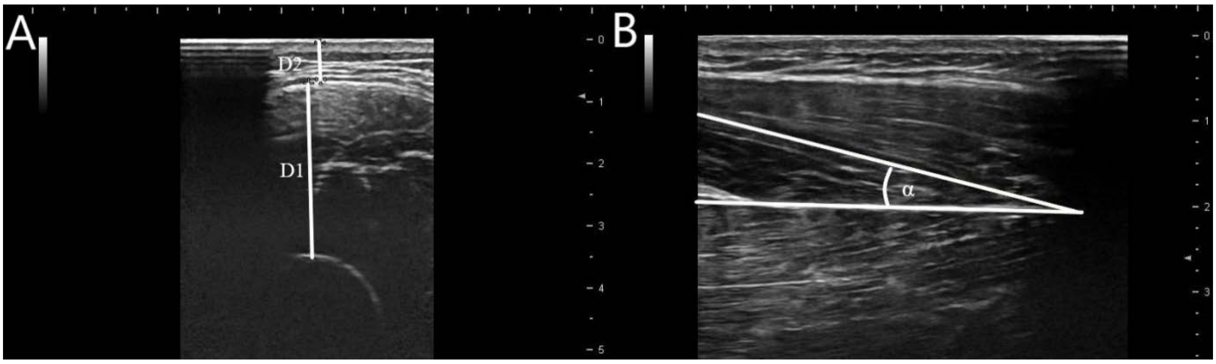

Table 1. Participants' training and competition history.

	Mean (95% CI)
General strength training experience (years)	7.5 (4.9, 9.9)
Powerlifting specific training experience (years)	3.6 (1.4, 5.8)
Powerlifting competition experience (years)	3.2 (1.1, 5.3)
Best competition result (squat + bench + deadlift; kg)	621.9 (565.8, 678)
Best competition result (Wilks points)	402.5 (365.8, 439.2)
Best competition bench press result (kg)	155.0 (142.2, 167.8)
Best competition bench press result (Wilks points)	99.1 (92.1, 106.1)

Table 2. Descriptive statistics (mean and 95% confidence intervals) and correlations (r) between structural factors and the dependent variable (Wilks points) along with statistical power.

Independent variable	Mean (95% CI)	Pearson's r (95% CI)	Power
Lean body mass – bioimpedance (kg)	77.7 (73.6, 81.8)	0.64*$ (0.14, 0.86)	0.7
Lean body mass – Mateigka (kg)	79.4 (75.1, 83.6)	0.7* (0.24, 0.9)	0.82
Lean body mass – ultrasound (kg)	68.9 (64.6, 73.1)	0.74* (0.32, 0.92)	0.87
Fat mass – bioimpedance (kg)	16.1 (12.9, 19.3)	–0.05 (–0.59, 0.52)	0.05
Fat mass – Mateigka (kg)	14.5 (10.6, 18.4)	–0.14 (–0.64, 0.45)	0.07
Fat mass – ultrasound (kg)	24.9 (19.1, 30.8)	–0.12 (–0.63, 0.46)	0.07
CSA agonist (mm)	119 (108, 130)	0.58* (0.04, 0.86)	0.59
Bone mass – bioimpedance (kg)	3.8 (3.6, 4)	0.65* (0.15, 0.88)	0.73
Forearm circumference (cm)	32.1 (30.9, 33.3)	0.7* (0.24, 0.9)	0.8
Upper arm circumference (cm)	38.7 (37.1, 40.3)	0.58* (0.04, 0.86)	0.59
Flexed upper arm circumference	41.3 (39.5, 43.1)	0.59*$ (0.06, 0.86)	0.6
Chest circumference (cm)	110.7 (107.3, 114.1)	0.15 (–0.44, 0.65)	0.08
Chest depth (cm)	20.0 (18.5, 21.6)	0.15 (–0.44, 0.65)	0.08
Arm span (cm)	182.7 (178.4, 187)	–0.02 (–0.57, 0.54)	0.05
Brugcsh index	0.62 (0.6, 0.64)	0.32 (–0.28, 0.74)	0.19
Ilio – acromial index	0.69 (0.67, 0.72)	–0.2 (–0.68, 0.39)	0.1
Brachial index	0.81 (0.79, 0.83)	0.6* (0.07, 0.87)	0.62
Arm length – height index	0.45 (0.44, 0.45)	–0.31 (–0.74, 0.29)	0.18

*$p < 0.05$; $ Spearman's ρ due to non-normal distribution of data.

Table 3. Descriptive statistics (mean and 95% confidence intervals) and correlations (Pearson's r) between technical factors (obtained at the point of minimal barbell velocity during the lifting phase) and the dependent variable along with statistical power.

Independent variable	Mean (95% CI)	Pearson's r (95% CI)	Power
Vertical bar displacement (cm)	26.7 (23.4, 30)	–0.31 (–0.74, 0.29)	0.18
Horizontal bar displacement (cm)	11.4 (8.4, 14.4)	0.24 (–0.36, 0.7)	0.12
Shoulder flexion angle (°)	43.1 (31.7, 54.4)	0.49 (–0.08, 0.82)	0.41
Shoulder abduction angle (°)	71.6 (64.9, 78.2)	0.47 (–0.11, 0.81)	0.39
Shoulder horizontal adduction angle (°)	28.4 (22.6, 34.1)	0.25 (–0.35, 0.7)	0.13
Elbow flexion angle (°)	48.7 (39.9, 57.6)	–0.4 (–0.78, 0.19)	0.27
Ground Force by the feet per kg/body mass (N)	9.4 (8, 10.7)	0.12 (–0.46, 0.63)	0.07
Lumbar arch height (cm)	10.4 (8.4, 12.3)	0.2 (–0.39, 0.68)	0.1

Table 4. Descriptive statistics (mean and 95% confidence intervals) and correlations (r) between neuromuscular factors and the dependent variable along with statistical power.

Independent variable	Mean (95% CI)	Pearson’s r (95% CI)	Power
MVC elbow extension (Nm)	378.2 (342.2, 414.2)	0.66* (0.17, 0.89)	0.74
MVC elbow extension (Nm/kg)	4.04 (3.70, 4.38)	0.54 (–0.02, 0.84)	0.51
Voluntary activation (%)	98.3 (97.2, 99.4)	0.18 (–0.41, 0.66)	0.09
Isokinetic shoulder flexion CON (Nm)	156.2 (135.2, 177.1)	0.71* (0.26, 0.91)	0.84
Isokinetic shoulder flexion CON (Nm/kg)	1.66 (1.49, 1.82)	0.64* (0.14, 0.88)	0.71
Isokinetic elbow extension CON (Nm)	129.7 (116.1, 143.3)	0.3 (–0.3, 0.73)	0.17
Isokinetic elbow extension CON (Nm/kg)	1.39 (1.23, 1.55)	0 (–0.55, 0.55)	0
Isokinetic horizontal shoulder flexion CON (Nm)	244.2 (223.5, 265)	0.57* (0.03, 0.85)	0.59
Isokinetic horizontal shoulder flexion CON (Nm/kg)	2.61 (2.41, 2.81)	0.36 (–0.24, 0.76)	0.23
Isokinetic shoulder flexion ECC (Nm)	183.5 (160.9, 206)	0.57* (0.03, 0.85)	0.59
Isokinetic shoulder flexion ECC (Nm/kg)	1.95 (1.77, 2.12)	0.44 (–0.15, 0.8)	0.34
Isokinetic elbow extension ECC (Nm)	164.3 (147.3, 181.3)	0.11 (–0.47, 0.62)	0.06
Isokinetic elbow extension ECC (Nm/kg)	1.77 (1.55, 1.98)	0.15 (–0.44, 0.65)	0.08
Isokinetic horizontal shoulder flexion ECC (Nm)	275.8 (247.6, 303.9)	0.09 (–0.48, 0.61)	0.06
Isokinetic horizontal shoulder flexion ECC (Nm/kg)	2.96 (2.64, 3.28)	–0.17 (–0.42, 0.66)	0.09
EMG pectoralis major (%)	129.1 (96.8, 161.5)	–0.09 (–0.61, 0.48)	0.06
EMG triceps brachii (%)	159.8 (139.2, 180.4)	–0.17 (–0.42, 0.66)	0.09
EMG anterior deltoid (%)	143.6 (123, 164.1)	0.22 (–0.38, 0.69)	0.11
EMG latissimus dorsi (%)	51.8 (36.7, 66.9)	–0.26 (–0.71, 0.34)	0.14
Pennation angle (°)	14.7 (13.5, 15.9)	–0.46$ (–0.81, 0.12)	0.46
Muscle fascicle length (mm)	82.7 (70.2, 93.2)	0.27 (–0.33, 0.71)	0.15

*p < 0.05; $ Spearman’s ρ due to non-normal distribution of data.

Table 5. Regression coefficients and standard errors.

Variable	B	SE_B	β
constant	24.628	58.6	
Lean body mass	0.812	0.397	0.515
Brachial index	–10.248	91.071	–0.031
Concentric isokinetic shoulder flexion	0.148	0.77	0.463

B – unstandardized regression coefficient, SE_B – standard error, β – standardised coefficient.