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Original Article

Predicting muscular strength using demographics, skeletal dimensions, and body composition measures

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ABSTRACT

The purpose of this study was to develop an equation to predict strength for seven common resistance training exercises using anthropometric and demographic measures. One-hundred forty-seven healthy adults (74 males, 73 females, 35 ± 12 yr, 174 ± 10 cm, 88 ± 19 kg) volunteered to participate. Body composition values (regional/total) and body dimensions were assessed using dual-energy x-ray absorptiometry (DEXA). Subjects underwent the following maximal strength assessments: Leg Press, Chest Press, Leg Curl, Lat Pulldown, Leg Extension, Triceps Pushdown, and Biceps Curl. Multiple linear regression with stepwise removal was used to determine the best model to predict maximal strength for each exercise. Independent predictor variables identified ($p < 0.05$) were height (cm); weight (kg); BMI; age; sex (0 = F,1 = M); regional lean masses (LM,kg); fat mass (FM,kg); fat free mass (FFM,kg); percent fat (%BF); arm, leg, and trunk lengths (AL, LL, TL; cm); and shoulder width (SW,cm). Analyses were performed with and without regional measures to accommodate scenarios where DEXA is unavailable. All models presented were significant ($p < 0.05$, $R^2 = 0.68$–0.83), with regional models producing the greatest accuracy. Results indicate that maximal strength for individual resistance exercises can be reasonably estimated in adults.

Introduction

Muscular strength reflects the muscle's ability to exert a maximal force on a single occasion, and is an important component of fitness and health.[1] A primary objective of health practitioners and strength training professionals is to develop the muscular strength of clients, rehabilitation patients, and athletes through implementing resistance exercise (RE) programs. To design such programs, it is critical to first obtain an accurate estimate of each individuals maximum muscular strength.[1,2] This is often achieved through one-repetition maximum (1 RM) testing, considered the standard for dynamic muscular strength assessment.[1,3] However, more conservative multiple RM tests are also employed, such as 3 and 5 RM tests. Completing these tests before initiating a RE program provides information on an individual's baseline strength, allowing for the determination of initial training loads.[1,3] Yet, even multiple RM tests may not be recommended in several situations such as large group exercise settings, testing of individuals with a low training age/training experience, functionally limited individuals, individuals engaged in post-operative/injury rehabilitation, and those with health-related contraindications to intense/high-load resistance exercise.[1]

Several biological, anthropometric, and fitness-related factors have been reported to influence muscular strength. In the general population, muscular strength tends to decrease with age due to losses of muscle mass—termed sarcopenia— in addition to cellular, metabolic, neural, and structural factors.[2,4–6] Lower levels of absolute strength are also observed in women compared to men, resulting from sex-related differences in body composition and fat-free mass distribution.[4] Considering anthropometrics, body mass is positively related to absolute muscular strength in a curvilinear manner,[7] while height may affect muscular strength via the influence of lever arm length on mechanical advantage during joint movements.[8] Similarly, in previous studies it has been demonstrated that anthropometric dimensions (limb lengths/widths and circumferences) may be related to the expression of upper and lower body strength.[9,10] Holding these factors constant, lean mass (soft tissue/muscle mass) and fat-free mass (non-fat soft tissue and bone mass) are positively related to muscular strength, explaining much of the inter-individual variability in maximum strength before and after

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Abbreviations:

DEXA	Dual-Energy X-Ray Absorptiometry
RE	Resistance Exercise
1 RM	One-Repetition Maximum
RM	Repetition Maximum
WT	Weight, kg
HT	Height, cm
BMI	Body Mass Index
%BF	Percent Fat
LM	Lean Mass, kg
FFM	Fat Free Mass, kg
FM	Fat Mass, kg
LegLM	Legs Lean Mass, kg
ArmLM	Arms Lean Mass, kg
TrunkLM	Trunk Lean Mass, kg
GynLM	Gynoid/Pelvic Region Lean Mass, kg
AL	Arm Length, cm
LL	Leg Length, cm
TL	Trunk Length, cm
SW	Shoulder Width, cm

RE.[11,12]

Although several methods exist to estimate muscular strength, few tools are available for health practitioners, clinicians, and strength training professionals seeking to: 1) design accurate beginning RE prescriptions when maximal testing may be ill-advised or impractical, 2) establish rehabilitation milestones for patients recovering from surgery or injury when pre-injury strength measures are not known, and 3) implement consistent testing procedures with regards to the progression of warm-up sets when strength measures are previously unknown. Considering this, an accurate method of estimating muscular strength without the need for direct strength testing would provide substantial value. Therefore, the purpose of this study was to develop equations to predict strength for seven common resistance training exercises using body composition measures in conjunction with anthropometric dimensions, age, sex, height, and weight for those with and without access to regional body composition measurement via dual-energy x-ray absorptiometry (DEXA).

Material and methods

Subjects

This study protocol was approved by the institutional review board of Texas A&M University (IRB2008-039). One-hundred forty-seven healthy untrained volunteers between 18 and 60 years of age (74 males, 73 females, 36 ± 12 yrs, 174 ± 10 cm, 88.0 ± 19.1 kg) (Table 1) were recruited from the local community via either email newsletter or word of mouth. Written informed consent was obtained from all subjects prior to participation following explanation of the benefits and risks of participation.

Procedures

Preliminary testing

Subjects arrived at the laboratory having avoided exercise for the previous 72 h and following a 10 h overnight fast; the bladder was voided immediately before any DEXA measures were completed. Hydration status was not assessed. Total and regional (arm, leg, gynoid) body composition values were assessed via dual-energy x-ray absorptiometry (Lunar Prodigy; GE Medical Systems, Madison, WI) with enCORE version 16 software. Height and weight were measured using a medical-grade scale (Seca Model 700; Seca, Hamburg, Germany, DEU). Body imaging provided by DEXA scan results was used in conjunction with ImageJ software (Version 1.8.0–172, NIH) to quantify anthropometric dimensions. The same trained technician administered and analyzed all DEXA scans. All subjects were positioned similarly during the scan, which was accomplished by measuring from the border of the scanning area to five different anatomical locations (heel, ankle, elbow, shoulder, and head) with the subject in the supine position. Regions of interest were initially automatically set by the software, and were then confirmed by the technician according to the training and instructions provided by the manufacturer.[13] Immediately following body composition assessment, all volunteers in this investigation were confirmed to be healthy enough for strenuous exercise via a Health and Lifestyle History questionnaire and a Bruce Protocol[14] maximal graded exercise test performed on a motorized treadmill with electrocardiography (Ultima, MGC Diagnostics®, St. Paul, MN). Our laboratory procedures for prescreening and stress testing, including the criteria required for a valid test, have been previously published.[14–16]

Table 1
Subject characteristics and performance variables.

	Males ($n = 74$)	Females ($n = 73$)	Total ($n = 147$)
Age (y)	35 ± 11	37 ± 12	36 ± 12
Height (cm)	181 ± 7	166 ± 6	174 ± 10
Weight (kg)	96.5 ± 16.1	79.3 ± 18.1	88.0 ± 19.1
Body composition			
Percent fat	30.0 ± 9.1	42.3 ± 10.0	36.1 ± 11.3
Fat mass (kg)	28.8 ± 12.5	33.3 ± 13.6	31.0 ± 13.2
Fat free mass (kg)	63.9 ± 6.4	42.5 ± 6.8	53.3 ± 12.5
Bone Content (kg)	3.7 ± 0.5	2.9 ± 0.4	3.3 ± 0.6
Anthropometric dimensions (cm)			
Arm length	56.7 ± 2.3	49.8 ± 2.5	53.3 ± 4.4
Leg length	98.6 ± 3.8	88.8 ± 4.1	93.8 ± 6.3
Trunk length	47.6 ± 1.8	44.7 ± 2.0	46.2 ± 2.4
Shoulder width	39.7 ± 1.9	35.3 ± 2.3	37.5 ± 3.1
Strength - 1 RM (kg)			
Leg press	431.1 ± 113.0	278.8 ± 81.7	355.5 ± 124.5
Chest press	70.1 ± 18.1	33.3 ± 8.3	51.8 ± 23.2
Leg curl	96.3 ± 19.1	61.9 ± 13.4	79.2 ± 23.8
Lat pulldown	90.1 ± 16.0	50.2 ± 10.5	70.3 ± 24.1
Leg extension	84.8 ± 20.1	50.5 ± 12.5	67.8 ± 24.0
Triceps pushdown	158.8 ± 43.5	93.2 ± 21.9	126.2 ± 47.6
Biceps curl	30.3 ± 7.6	13.9 ± 4.2	22.2 ± 10.3
Total	961.4 ± 207.8	581.8 ± 133.1	772.9 ± 258.1

[a] Values are presented as means ± SD.
[b] Sex differences observed for all variables ($p < 0.05$) with the exception of age.

Strength assessment

At least 72 h after the VO_{2max} and DEXA assessments, subjects completed strength testing to determine their 3–5 RM on Keiser® pneumatic resistance training equipment (Keiser Corporation, Fresno, CA). A complete description of Keiser® equipment is published in previous literature.[17] Seven resistance training exercises were assessed in this order: Leg Press, Chest Press, Leg Curl, Lat Pulldown, Leg Extension, Triceps Pushdown, and Biceps Curl. Prior to the assessment, subjects performed a standardized warm-up protocol involving 3 min of light stationary cycling followed by a series of standardized whole-body stretching exercises used by our laboratory in previous investigations.[18] Procedures for performing strength testing, and for calculating the 1RM of each exercise, were adapted from Baechle and Earle.[3] The reliability of these methods for determining the 1RM has been confirmed by previous research.[19–21]

Statistical analysis

All data analysis was performed using IBM SPPS Statistics for Windows (Version 25.0. Armonk, NY: IBM Corp). Two-tailed, unpaired t-tests were used to determine whether significant differences existed between

males and females in demographics, body composition, and maximal strength (Table 1). Multiple linear regression with stepwise backward removal was used to develop prediction models for maximal strength for each RE. Models were selected based on the highest adjusted R^2 and lowest degree of variance inflation. Independent variable coefficients included in each prediction model were selected based on significance within the model. To accommodate testing scenarios where DEXA may not be available, analyses were performed both with and without regional measures. The level of significance for all statistical measures was held at an alpha level of 0.05. The data for all demographic and RE variables are reported as mean ± SD.

Results

Significant differences were observed between genders for all variables with the exception of age ($p < 0.05$, Table 1). Regression analysis results are displayed in Figs. 1 and 2 for prediction models of maximal strength, both excluding and including regional DEXA measures, respectively. Stepwise removal identified height (cm), weight (kg), BMI, age, sex (0 = F,1 = M), regional lean masses (LM, kg), fat mass (FM, kg), fat free mass (FFM, kg), percent fat (%BF), skeletal dimensions [arm length (AL), leg length (LL), trunk length (TL) and shoulder width (SW), cm] as independent predictor variables ($p < 0.05$). All models presented were found to be significant ($p < 0.05$), with the R^2 for the equations indicating that approximately 68%–83% of the variance in maximal muscular strength is explained by the independent variables included in

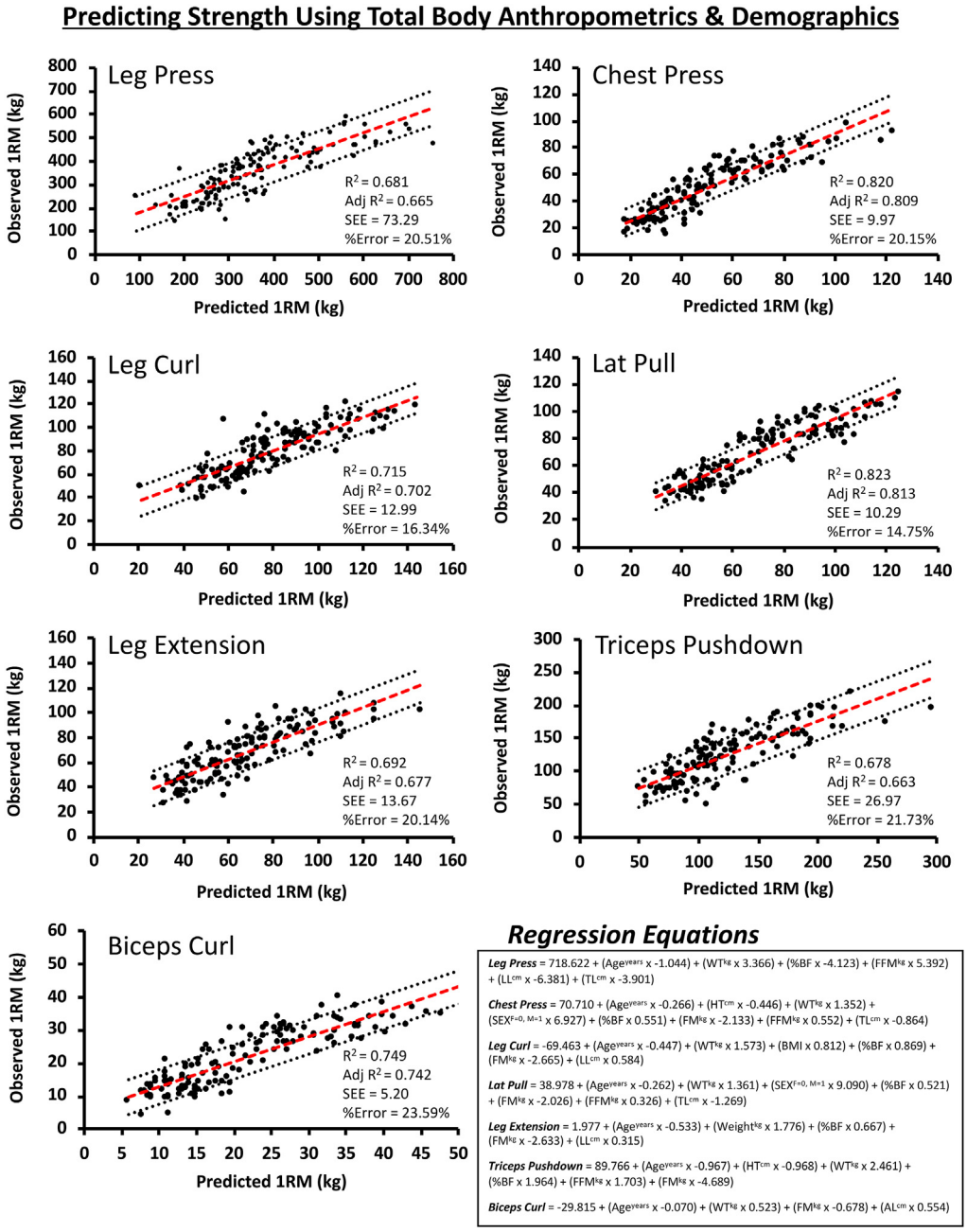

Fig. 1. Prediction models including total DEXA measurements in conjunction with anthropometric dimensions and demographics. Presented for maximal strength on the following exercises: Leg Press, Chest Press, Leg Curl, Lat Pulldown, Leg Extension, Triceps Pushdown, and Biceps Curl. All models were found to be significant at $p < 0.05$.

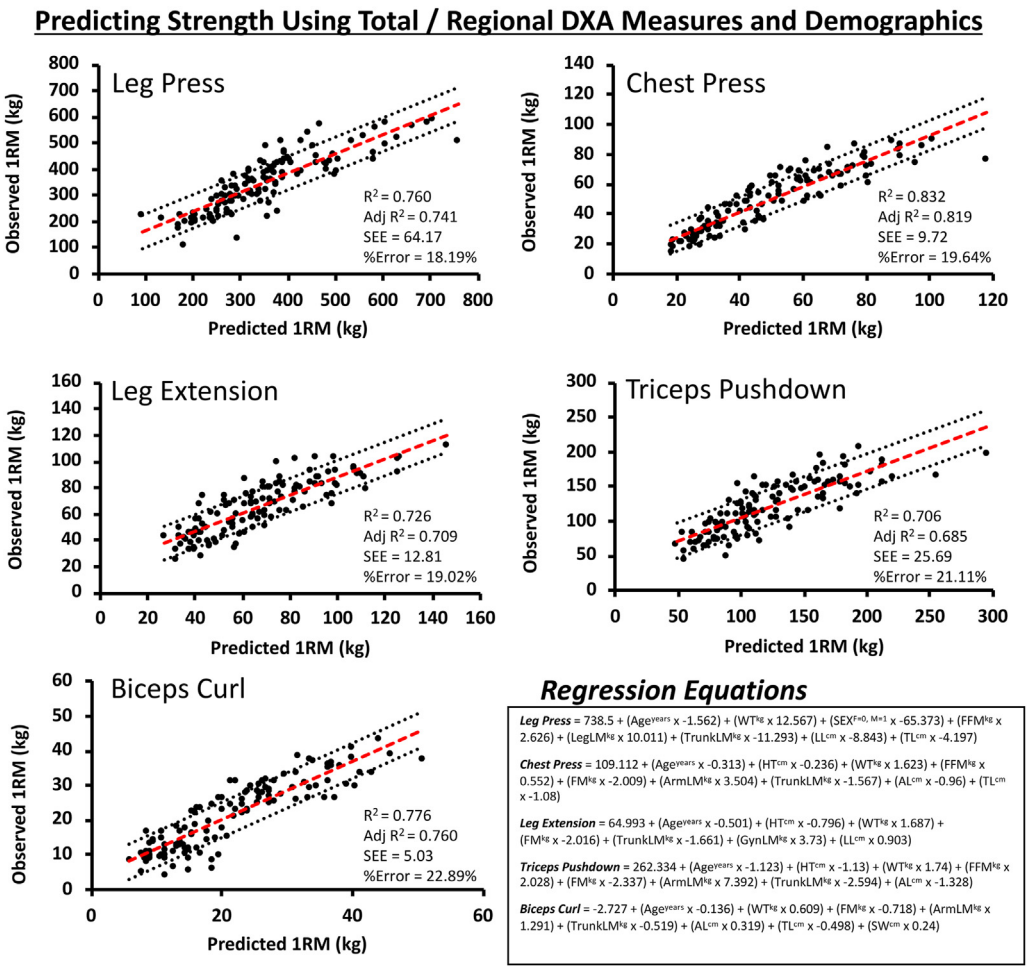

Fig. 2. Prediction models including total/regional DEXA measurements in conjunction with anthropometric dimensions and demographics. Presented for maximal strength on the following exercises: Leg Press, Chest Press, Leg Extension, Triceps Pushdown, and Biceps Curl. Lat Pulldown and Leg Curl not displayed because inclusion of additional regional DEXA measures did not improve the predictive accuracy of these equations. All models were found to be significant at $p < 0.05$.

each model. The predictive accuracies of equations for Lat Pulldown and Leg Curl were not improved by the inclusion of additional regional DEXA measures. For the remaining exercises, higher R^2 values indicate that prediction equations utilizing regional measures of LM provided greater predictive accuracy compared to the inclusion of total body composition alone (Fig. 2).

Discussion

The development of muscular strength promotes the maintenance and improvement of bone mass, muscle mass, musculotendinous integrity, resting metabolic rate, glucose tolerance, and the capacity to complete activities of daily living.[1] Thus, it is a critical component of health and physical fitness. The purpose of this study was to develop equations to predict strength for seven common resistance training exercises using body composition in conjunction with anthropometric and demographic measures, for those with and without access to DEXA. Maximal muscular strength was accurately predicted using body composition variables combined with anthropometric dimensions (arm, leg, and trunk lengths; shoulder width), age, sex, height, and weight ($R^2 = 0.68–0.83$; Figs. 1 and 2). Excluding Lat Pulldown and Leg Curl, regional prediction models yielded higher R^2 values likely due to the specific inclusion of muscle groups used for each exercise (ex: Legs and Trunk LM used to predict Leg Press maximal strength). However, for all exercises, total FFM was still found to be predictive of strength ($p < 0.05$) and may be utilized in the absence of regional measures to estimate muscular strength.[22]

Practical utility

A primary goal of health practitioners and strength training professionals is to design progressive RE programs aimed at developing muscular strength in a variety of individuals, ranging from the general population to elite athletes. It is, therefore, necessary for these practitioners to have an accurate understanding of the maximum muscular strength of their athletes and clients, either through direct measurement or estimation.[1,2] Tests that are commonly employed among practitioners to directly measure maximal strength include the 1 RM and various multiple repetition maximum tests, such as the 3 and 5 RM.[3] However, several situations exist in which these assessments are ill-advised or unreasonable.[1] In these cases, the prediction equations developed herein for the estimation of maximal muscle strength of seven common resistance exercises may be applied.

In particular, these findings may assist in exercise programming for large groups or for individuals where direct measures of strength are not feasible or recommended for initial RE prescription. Additionally, these models allow for the standardization of warm-up sets during strength testing of first-time clients or research subjects when strength measures are previously unknown. When strength development or muscle performance is the primary research outcome, this improved consistency mitigates the normally large degree of initial variability in data collection introduced by basing warm-up sets on subjective assessments of effort/exertion. Moreover, in the rehabilitation setting, patient information regarding muscle strength prior to injury is often unavailable in the

general population. In effect, a classification of a recovering patient as "fully functional" relative to before their injury is often arbitrarily determined rather than based on established standards. Thus, these prediction models may be applied by therapists to establish post-operative/injury rehabilitation milestones. Specifically, therapists may develop target ranges for muscle strength using the standard errors of the predicted values, allowing for a systematic determination of patient functionality.

Regression coefficients

The independent predictor variables selected for inclusion in the prediction equations have all been previously demonstrated to influence muscular strength measures. In all equations derived, consistencies were observed in the relationships of age and weight to the prediction of muscular strength. Considering age, a negative relationship with maximal strength existed in all prediction equations. This is consistent with reports of age-associated decreases in muscular strength and functional decline beginning primarily at ~45 years of age.[2,4] Not surprisingly, body weight was included as a positive coefficient in all regression models. This is understandable, given the positive curvilinear relationship reported between this variable and absolute muscular strength.[7] Additionally, the inclusion of sex in Chest Press and Lat Pulldown prediction models excluding regional measures indicates a higher strength estimation in males, while the opposite was observed in our regional Leg Press model. This finding may be due to the explanation of variance related to potential sex-based differences in tissue distribution in the general population (Table 1).[4] Moreover, at least one length or width measure was included in all but one prediction equation. In general, the relationship appears to be related to the single- or multi-joint classification of exercises. For example, measures that were positive predictors of strength were solely included in equations for single-joint exercises. Conversely, all equations predicting strength in multi-joint, complex exercises (Leg Press, Chest Press, and Lat Pulldown) included only negative length or width coefficients. At the base level, the observed negative relationship is understandable due to the longer lever arms, and thus greater torque requirements, of longer limbs. However, a precise reason for the differential relationships between exercise types is unclear, and is potentially related to the influence of body dimensions on mechanical advantage in conjunction with the varying degree of complexity of exercises.[8]

The relationship between muscle mass and strength is well-established, and is shown to be positively associated with muscular strength independent of the hypertrophy-inducing effects of RE.[11,12] The results of this study confirm this relationship, as indicated by the positive relationship observed between maximal strength and total FFM in all prediction equations including this variable. A positive relationship also existed between arm, leg, and gynoid LM in the prediction of maximal strength, consistent with the above finding. Likewise, several models excluding regional DEXA measures incorporated %BF as a positive coefficient. We hypothesize that this is related to the rise in lean body mass that occurs with increases in body mass and adiposity.[4] Additionally, it is possible that body mass and fat distribution influence mechanical leverage and stability. However, future studies are needed to evaluate these measures in relation to the biomechanics of performing resistance exercise.

Limitations

This study is not without limitations. The age range of subjects recruited for this study was limited to 18–60 years of age, and the accuracy of our equations, therefore, cannot be confirmed in younger or older populations. Similarly, due to the sample population availability, we were not able to determine if ethnicity may contribute to further strengthening of these models, and whether or not ethnicity-specific predictions may be warranted. Moreover, training history was not included in these models. As this is a categorical variable derived from a subjective, survey-based question, it is possible that its inclusion would have introduced a high degree of variance. Therefore, further study validating these models in different ethnicities, and in trained and untrained populations, may be worthwhile. Also, the Keiser® resistance training equipment used in this study does not utilize the same mechanical loading systems as some other common RE equipment. Future studies will be required to determine the validity of these models on various types of equipment (plate loaded, pin select, etc.) and whether or not equipment type should be included or considered in future prediction models. Despite this, the applicability of these prediction equations across RE equipment is suggested by the similarities in the major muscle groups involved and in the mechanics of the movement patterns. Comparing Keiser® and free weight equipment, the findings of one study revealed that the difference in 1 RM between these RE systems is less than 10%.[23] Additionally, a potential limitation arises out of the use of DEXA for body composition analysis to develop our prediction equations. Specifically, DEXA machines may not be readily accessible for many health and fitness practitioners. However, in these situations, anthropometric and demographic variables can be used to estimate total and regional DEXA body composition in various populations.[22,24–29] Moreover, physiologic factors such as fiber-type distribution and muscle pennation were not observed. While we do not dispute that these factors may be predictive of strength,[12,30] collecting such data was impractical for the purposes of this study. Lastly, we cannot discount that prior testing for one particular exercise may affect performance on subsequent exercises during the assessment. However, this study protocol minimized this effect through alternating between upper/lower body and agonist/antagonist exercises. Additionally, exercises progressed from large muscle group multi-joint exercises to smaller muscle group single-joint exercises as commonly recommended during strength assessment and training.[3]

Conclusions

We have developed a series of novel prediction equations to estimate the maximal strength of seven common RE, both with and without regional body composition measures. Due to the novelty of the present research, it is difficult to compare the utility of these prediction equations to other methods of estimating maximal strength. Yet, this study demonstrates that maximal strength may be accurately predicted using DEXA body composition variables in conjunction with anthropometric dimensions, height, weight, age, and sex. Importantly, total body composition measurements are still applicable for the prediction of maximal strength in the absence of regional measures. Further investigation will be required to determine the efficacy of applying these models to other types of equipment or if specific predictions equations may be required for differing equipment brands.

Authors' contributions

Sean T. Stanelle wrote the Primary manuscript, and reviewed literature. Sean T. Stanelle , Tyler R. Heimdal , Alexandra L. Remy and Bradley S. Lambert collected and analyzed the data. Stephen F. Crouse and Steven E. Riechman were responsible for the project, designed the study, and supported laboratory facility and equipment. Stephen F. Crouse, Tyler R. Heimdal and Bradley S. Lambert developed the manuscript. Sean T. Stanelle and Bradley S. Lambert generated the manuscript tables and figures. Bradley S. Lambert was the project director and responsible for statistics.

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and the National Strength and Conditioning Association (Colorado Springs, CO). Funding sources had no involvement in study design, data collection, data analysis, interpretation of data, manuscript development, or in the decision to submit the paper for publication.

Ethical approval statement

The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The procedures were approved by the institutional review board for research involving human subjects (IRB2008-039), and all volunteers signed a written informed consent prior to participating in the experimental procedures. The manuscript has not been published and is not under consideration for publication elsewhere.

Submission statement

The manuscript has not been published and is not under consideration for publication elsewhere.

Conflict of interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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