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A comparison between measured female linear arm strengths and estimates from the 3D Static Strength Prediction Program (3DSSPP)

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ABSTRACT

This study performed a direct comparison between empirically measured female linear arm strengths and those estimated with the 3D Static Strength Prediction Program (3DSSPP). Linear arm strengths were collected from 15 female participants, at four hand locations and six primary directions (n = 360), and then estimated with 3DSSPP incorporating each participant's own segment lengths, body masses and joint strengths, and the measured arm postures from each trial to optimize the accuracy of 3DSSPP. In spite of this, the errors in 3DSSPP's estimated arm strength values were very high (RMS error = 56.0 N and 40.4%) and poorly correlated (r^2 = 29.2%) with measured strengths. These results seriously question the accuracy of 3DSSPP to estimate female linear arm strengths and percent capable values, for the range of conditions tested, likely due to the overly simplified assumptions made to estimate triaxial shoulder strength.

1. Introduction

Most occupational tasks place arm strength demands on the upper extremities via linear forces and/or torques applied to the hand(s). There is a higher risk of workplace musculoskeletal disorders (WMSDs) when the manual forces result in upper extremity joint torque demands that exceed joint strength capacities (Bernard, 1997; Keyserling, 2000; Yassi, 2000). In the U.S., in 2019, there were 284,860 injuries to the upper extremities causing days away from work in the private sector. Of these reported injuries, 67,020 occurred at the shoulder and had a median of 28 lost days per incident - almost double that of the wrist (15) which was the next highest (National Safety Council, 2020).

Commercial digital human model ergonomics software packages are available to estimate the relative strength demands on the elbow and shoulder joints caused by torques or linear forces applied at the hands. These include the 3D Static Strength Prediction Program (3DSSPP, University of Michigan, Ann Arbor, MI), Jack and Process Simulate (Siemens, Ann Arbor, MI), Santos (SantosHuman, Inc., Coralville, IA), Delmia (Dassault Systèmes, Vélizy-Villacoublay, France) and others. These software packages generally use inputs of body mass and joint locations to calculate estimates of segment mass and center of mass locations. A linked-segment model and the magnitude and direction of forces are then used to calculate static joint reaction moments, joint strength 50th percentile and standard deviation values and, ultimately, the percent capable of the strength demands on various joints of the body, so that the limiting load and joint can be determined for the target population percentage.

This paper focusses on the 3DSSPP software package, and the method it uses to estimate linear arm strengths (LAS), and the percentage of the population capable of exerting specified linear force demands, based on estimates of static, uniaxial elbow and triaxial shoulder strengths. The 3DSSPP software makes two important assumptions, when estimating triaxial shoulder strength, that may be overly reductive and appear to have no scientific evidence to support them: (1) the effects of independent rotations about the three shoulder axes do not have interacting effects on shoulder strength, and (2) the strength about one axis does not depend on the demands about the other two axes.

In spite of 3DSSPP's prevalent use by ergonomists to estimate percent capable values for linear arm strength demands, and potential oversimplifications in its approach for calculating triaxial shoulder strengths, we are aware of no published data to directly verify the outputs of their model for this purpose. However, there have been some

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Abbreviations: 3DSSPP, 3D Static Strength Prediction Program; JAS, joint axis strength; LAS, linear arm strength; RMS, root mean square; WMSD, workplace musculoskeletal disorders.

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indirect comparisons between model estimates and previously published linear arm strengths from empirical studies where the participant's postures and joint axis strength (JAS) characteristics were unknown. Garg and Chaffin (1975) compared their model's estimates to previously published male strengths from Thordsen et al. (1972) and the average and RMS errors were −45.2 N and 140.2 N, respectively. Chaffin et al. (1987) compared the model's estimates to measured LAS (Rohmert, 1966) and the average error was −3% and the explained variance was only 50%. Chaffin and Erig (1991) compared the model estimates with measured LAS values from Warwick et al. (1980) and found average and RMS errors of +13.6 N and 25 N, respectively (see Appendix A for more details).

These errors are cause for concern, but it is possible that a more direct comparison between measured strengths and estimates from 3DSSPP using the specific participant anthropometry, postures and elbow and shoulder joint axis strengths, would provide more encouraging results. The purpose of the current study was to perform such a comparison for female strength, as the 75% capable female criterion by NIOSH (Waters et al., 1993), is used for most assessments in North America. We believe that approach affords 3DSSPP the best opportunity to produce accurate LAS estimates, such that it will result in serious questions about the validity of 3DSSPP, for this purpose, if large errors are still observed, at least within the range of task conditions evaluated.

2. Material and methods

2.1. Study overview

This study was comprised of four components: (1) the collection of joint axis strengths (JAS) about one axis at the elbow and three axes at the shoulder, (2) the collection of linear arm strengths (LAS) in six directions at four hand locations, (3) the estimation of LAS values using the 3DSSPP software customized with each participant's segment lengths, body mass, JAS values and right arm postures for each condition, and (4) a calculation of the errors in the 3DSSPP LAS values compared to those measured directly in the lab.

2.2. Participants

A total of 15 right-hand dominant, healthy females, were recruited for this study (mean stature = 1.692 ± 0.083 m, body mass = 63.2 ± 12.7 kg, age = 24.0 ± 2.0 years). These participants were free of any upper body acute injuries and/or chronic disorders for a period of at least one year prior to the onset of data collection.

Prior to the commencement of the study, participants were required to read and sign a written consent form explaining the protocol approved by the university's ethics board. We measured the length of the upper arm (mean = 0.294 ± 0.022 m), forearm (0.256 ± 0.020 m) and distance from the wrist to the "knuckle" (0.088 ± 0.011 m) to facilitate customization in 3DSSPP for each participant. For the purposes of this paper, we will define the "knuckle" as the metacarpophalangeal joint of the second/middle finger.

2.3. Instrumentation and data acquisition

A custom laboratory apparatus was constructed with two stabilized vertical slotted rails and a horizontal slotted rail that could be moved vertically and secured between them (80/20 Inc., Columbia City, IN). For all JAS and LAS trials, participants were secured into a chair with a lap belt and shoulder straps, and the chair was secured to a wood platform that was then secured to the slotted rail structure. For the abduction and adduction JAS conditions (described later), force was measured with the participant's upper arm secured onto a padded brace, which was fastened to a triaxial load cell platform (500 lbs. XYZ Sensor, Sensor Development Inc., Lake Orion, MI) that could be moved horizontally and secured to the height-adjustable horizontal rail. For other JAS conditions (described later) a uniaxial force transducer (100 lbs., Omegadyne Inc., Laval, QC, Canada) was connected between the slotted rail structure and a padded cuff around either the wrist or the forearm near the elbow.

For the LAS trials, the padded brace was removed from the triaxial load cell and replaced with a fixture with a padded, vertical handle. Also, joint locations of the right shoulder, elbow, wrist and knuckle were measured using the 6-degree-of-freedom FASTRAK electromagnetic system (Polhemus, Colchester, VT). Sensors were affixed (1) at the shoulder over the acromion process, (2) at the elbow over the lateral epicondyle, (3) over the middle of the dorsal surface of the forearm, and (4) over knuckle as defined previously. This allowed for the determination of the joint locations and joint angles throughout the LAS collection.

Custom LabVIEW software (National Instruments, Austin TX) was used to acquire all data with a 12-bit A/D card (National Instruments, Austin TX) on a PC computer. Force data were sampled at 120 Hz, and the FASTRAK kinematic signals were sampled at 30 Hz. Participants received visual feedback of the direction and magnitude of the recorded forces throughout each JAS and LAS trial, from a computer monitor placed in front of them.

We used the same coordinate system, joint posture definitions and joint strength demand conventions as 3DSSPP, and these are summarized in Appendix A and Fig. 1.

2.4. Experimental procedures and protocol

Data collection for each participant in this study was completed over the course of two 1-h sessions. The order of completing the JAS and LAS protocols was counter balanced. During the first session, anthropometric measurements were made, then participants were familiarized with the first assigned protocol (JAS or LAS), and then they completed that protocol. During the second session, the participant was familiarized with the remaining protocol (JAS or LAS), and then they completed that session's protocol. Participants were provided with a minimum of two days of rest in between the two testing sessions, to account for any fatigue effects.

2.4.1. Elbow and shoulder joint axis strengths (JAS)

We replicated, as closely as possible, the postures, force application locations and effort directions used by Stobbe (1982) for elbow and shoulder JAS measurements (Fig. 1). Specifically, we measured elbow extension and flexion strengths, as well as the following six shoulder strengths: abduction & adduction, backward & forward horizontal, and lateral & medial humeral.

Before all JAS trials, participants were seated and firmly strapped into the chair using a waist strap and a strap that came over the left shoulder and crossed the chest (Fig. 1). For shoulder abduction and adduction strengths, the forearm was secured to a padded cuff over the triaxial load cell. For the other six conditions, a padded cuff was attached around the wrist (for both elbow and both humeral JAS efforts) or around the upper arm proximal to the elbow (for shoulder abduction and adduction JAS efforts). The cuffs were connected to stiff cables and rope to either the uniaxial force transducer (both elbow and humeral efforts) or triaxial load cell (both horizontal efforts) and then to the slotted rail apparatus, at 90° to the segment of attachment. Moment arms to the joint of interest were recorded so that moments of force could be calculated as the product of the measured force and moment arm to represent the JAS.

During the JAS trials, participants slowly ramped the force to maximum over 1–2 s, held the maximum for at least 1 s, and ramped back down over 1–2 s. During the exertions that were measured with the upper arm secured to the cuff on the tri-axial load cell (abduction, & adduction), participants were provided with visual feedback indicating the direction and magnitude of the forces applied so we could ensure that at least 90% of the resultant force was in the intended direction - if

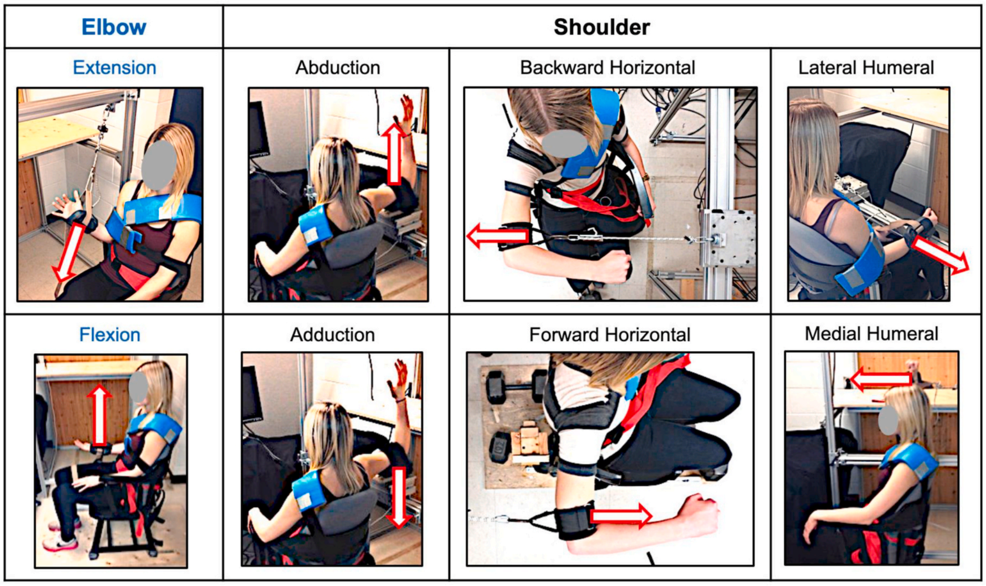

Fig. 1. Summary of the joint axis strength protocols used to replicate the Stobbe (1982) elbow and shoulder strength measurements. The posture, straps harnessing to the chair, location of padded cuffs and connection to the force transducer are shown for each of the 8 joint axis strength tests.

not, the trial was recollected. For all JAS exertions using a wrist cuff connected to a cable, only the force magnitude was provided. At least 90-s of rest was provided between each trial to abate any fatigue effects. Three repeat trials were collected for each of the 8 joint axis strength conditions.

2.4.2. *Linear arm strength (LAS)*

A description of our materials and protocol for collecting manual arm strengths has been presented previously (La Delfa et al., 2014; La Delfa and Potvin, 2016, 2017) but will be described briefly along with details specific to this study. Prior to testing, the four FASTRAK sensors were affixed to the right arm and the source was located on a post on the chair, position posterior and lateral to the right shoulder. The participant was then seated in the chair facing parallel to the apparatus, with the participant secured with the waist and shoulder straps. Participants were able to reach the handle within the reach envelope of their right hand, allowing for a comfortable wrist/arm posture for the various hand locations and exertion directions. The slotted rail apparatus could be adjusted to move the hand into the required anterior, inferior/superior and lateral location, with respected to the right shoulder, which served as the reference location (Fig. 2).

Each participant's LAS was evaluated at all combinations of four hand locations and six exertion directions, for total of 24 conditions. The six primary directions were studied: anterior (push forward), posterior (pull backward), superior (push upward), inferior (push downward), lateral (push right) and medial (push left). Participants' wrists were either positioned within the handle or coupled to the handle using a padded wrist strap and hooks. These methods of coupling to the wrist were implemented so that LAS data could be collected while the participants' wrist strength was not a limiting factor.

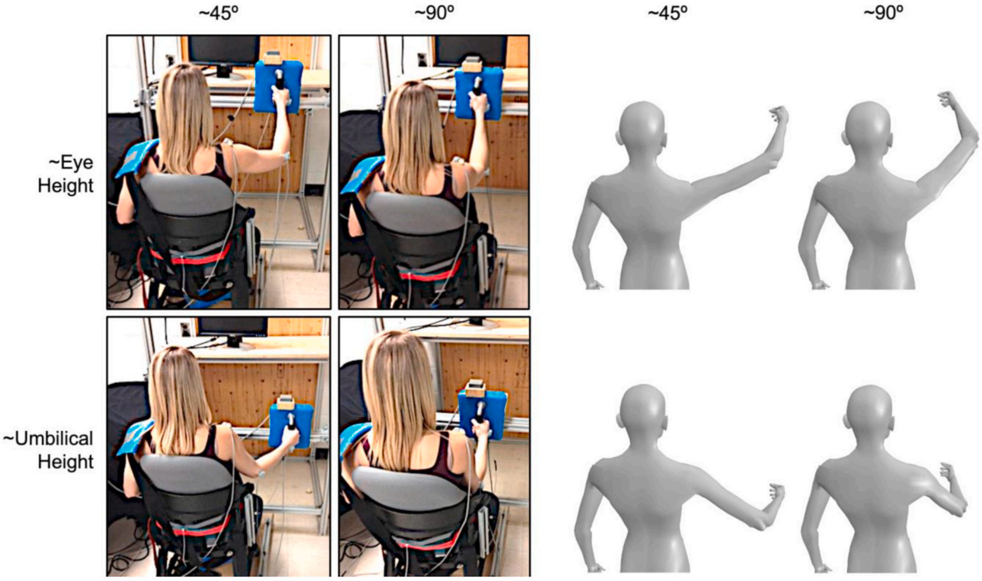

Fig. 2. (Left) Photos of the experimental setup for collecting linear arm strength at the four combinations of the two knuckle heights and two arm rotations for the anterior efforts. (Right) The 3DSSPP manikin postures for the four combinations with the knuckle at the average coordinates and the elbow at the average heights, pooled across all directions and participants (see Table 1).

The hand locations were defined by the location of the "knuckle" relative to the center of the glenohumeral joint of the shoulder. The four hand locations were based on the height of the knuckle and the angle that the line from knuckle-to-shoulder made with the frontal plane. The knuckle was placed in one of four hand locations, including all combinations of approximately eye or umbilicus height, while seated, and rotated ~45° or ~90° (ie. in front of the shoulder) from the frontal plane. The reach was calculated as the distance from the shoulder to knuckle, when the arm was fully extended with a neutral wrist and was always approximately 80% of this maximal reach distance (Fig. 2).

Given the focus on the elbow and shoulder in the current study, our previous protocol was modified to remove the wrist and forearm from limiting the LAS (Fig. 3). A padded cuff was wrapped around the forearm, just proximal to the wrist joint. For three of the four hand locations, and for forces applied in the frontal plane (inferior, superior lateral and medial), the wrist and padded cuff were secured within a handle attached to the triaxial load cell. For the frontal plane force at approximately eye height and ~90°, this method resulted in awkward hand posturing, so different methods were used - superior, inferior and medial force used a hook attached to the wrist cuff on one end and the handle on the other, while the lateral force required the participant to push into the handle with the cuff over the dorsal surface of the wrist. For anterior efforts in all four hand locations, the participant made a fist and pushed forward on the surface of the first metacarpals. For posterior efforts in all four locations, participants pulled back on a hook connecting the wrist cuff and load cell handle (Fig. 3).

Trials were blocked on hand location, presented in a random order, and then the order of the six directions were randomized within each hand location. As with the JAS trials, participants slowly ramped the force to maximum over 1–2 s, held the maximum for at least 1 s and ramped back down over 1–2 s, and they were provided with visual feedback on the direction and magnitude of the current force application. Participants were instructed to apply the force only in the intended direction and trials were discarded and repeated if the force in that direction was not at least 90% of the resultant force magnitude. At least 90-s of rest were provided between each trial to abate any fatigue effects. Three repeat trials were collected for each of the 24 linear arm strength conditions.

2.5. Data analysis

2.5.1. Joint angle and linear arm strengths

Signals from both the uniaxial force transducer and triaxial load cell were first digitally filtered with a 1-s moving average. For both the JAS and LAS tests, the highest of the three repeat trials was used to represent the strength of each participant, and only force components in the intended direction were considered. The highest linear forces, measured during the joint strength trials, were multiplied by the moment arm to the right shoulder joint to calculate JAS values as moments of force.

2.5.2. Estimating the joint center locations

Joint locations were estimated based on magnetic sensors positioned superficially on the skin, and further calculations were made to estimate the shoulder, elbow, wrist and knuckle joint centers. Shoulder and elbow joint centers were estimated using the procedure outlined by Nussbaum and Zhang (2000). A different method was necessary for the wrist and knuckle locations because the padded wrist cuff prohibited positioning of the sensor over the wrist joint and the anterior LAS condition prohibited positioning the hand sensor directly over the knuckle (Fig. 3). For the wrist, a virtual location was first determined, based on anthropometric measurements, extrapolating a line from the elbow sensor to the sensor on the dorsal surface of the forearm, the length of the forearm, then moving perpendicular to that line, towards the palm, half the distance between the dorsal and palmar surface of the participant's wrist. The knuckle location was estimated by extrapolating the line from the elbow to the wrist, by the distance measured from the wrist to the knuckle measured for each participant.

2.5.3. 3DSSPP calculations for estimating shoulder and elbow strength

The approach used by 3DSSPP to predict elbow and shoulder strength, and the percent capable values associated with the strength demands about each axis, have been described previously (Chaffin et al., 1987; Chaffin and Erig, 1991; Garg and Chaffin, 1975) and is summarized in Appendix. A unique manikin was established in 3DSSPP for each of the 15 participants, using their own body mass and the average stature across the 15 participants (1.692 m). This allowed for a consistent location of the right shoulder (0.1781, 0.0291, 1.3804 m) to be used as the reference for hand locations. Next, we used the <Task Input>, <Anthropometry>, <Display/Modify Anthropometry Values>, <View Right Side Values> options to change the length of the right Hand Grip Center, Lower Arm and Upper Arm to the lengths from wrist to knuckle, lower arm and upper arm, respectively, measured on the participant. Finally, we used the <Task Input>, <Anthropometry>, <Modify Population Factors>, <Edit Population Factors> (unlocked with the password provided in the 3DSSPP user's manual), and <Actual Value> options to customize the two elbow and six shoulder strengths to those measured for the participant during the JAS protocol.

Once the manikin was established for a participant, it was used to replicate the measured arm posture and hand location for each of the 24 conditions. In 3DSSPP, it is not possible to both lock the trunk upright and precisely specify the right-hand location with their <Posture Prediction> function. So, the trunk was locked and the lateral (x), horizontal (y), and vertical (z) locations of the hand locations were changed by dragging them in the "Stick-View" windows. But, in the 2D windows, using a mouse to change the coordinate for one axis inevitably resulted in small changes coordinate of the other axis. So, we moved the right

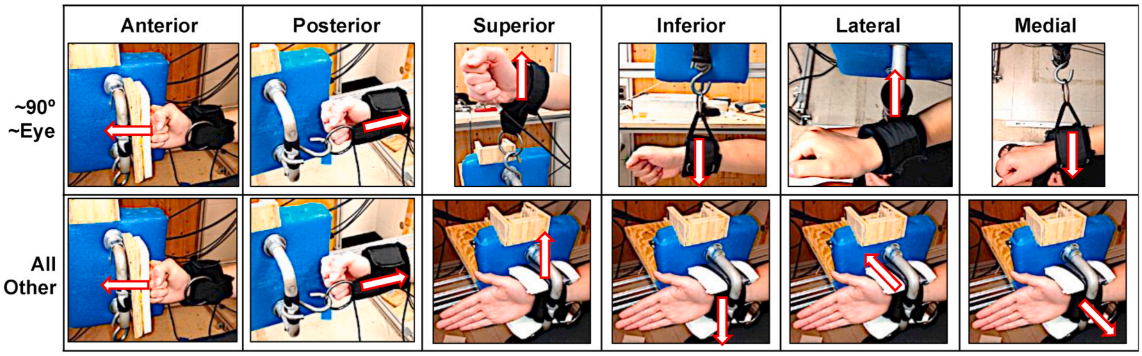

Fig. 3. The linear arm strength interfaces are shown for each of the six directions. These were the same for anterior and posterior forces in all four hand locations. For locations at approximately eye height and ~90°, forces were applied outside the load cell handle, either directly or with a hook connecting the wrist cuff and handle. For the remaining three hand locations, the superior, inferior, lateral and medial efforts were performed with the wrist and padded cuff within the load cell handle.

knuckle to within 0.005 m of the intended location for each axis. We assumed the wrist remained in the neutral posture for all assessments. With the hand now locked in place, the elbow was rotated up or down to the height measured during the trial (relative to shoulder height) and, since the participants' actual segment length were customized into 3DSSPP, this allowed us to match the actual hand location and joint postures as closely as possible given the constraints of data entry in the software. Hand coordinates and elbow heights were determined based on the standardized location of the right shoulder (defined above).

A separate analysis was performed using a manikin with the average subject stature of 1.692 m and mass of 63.2 kg and the default strengths in 3DSSPP v7.1.3. The average hand location and elbow height, pooled across participants, were calculated for each of the 24 conditions and used to position the right hand and set the right elbow height as described above. This resulted in 24 LAS values from 3DSSPP that could be compared to the mean of the measured LAS values for each condition.

One rater initially performed all 360 assessments (24 conditions x 15 participants) in 3DSSPP. A second rater then performed an independent assessment of all 360 conditions and identified and corrected any errors in the hand location, elbow height, and force direction or the determination and recording of LAS and limiting axis, though such corrections were only required for 6 of 360 (1.7%) cases. The verified and corrected 3DSSPP LAS values and limiting axes were used for all subsequent statistics.

2.6. Statistical analysis

Mean and standard deviation values were calculated for each of the 8 measured JAS conditions, pooled across the 15 participants. The 3DSSPP estimates of LAS were compared to the measured LAS values in several ways. For each of the 24 conditions for each of the 15 participants (n = 260) error values were calculated as the 3DSSPP estimates minus the measured values and percent errors were calculated with that error divided by the measured LAS. Correlations were also calculated between the two values and squared to determine explained variance. The axis/direction limiting the LAS value in 3DSSPP was recorded. With these values, we determined the mean and RMS errors, r-squared values, and relative frequency of each axis/direction being limiting, across all conditions and participants (n = 360), and pooled within each of the 2 heights (n = 180) and 2 angles (n = 180), each of the 4 hand locations (n = 90), each of the 6 directions (n = 60), and each of the 24 conditions (n = 15).

3. Results

3.1. Hand locations

The means of the right knuckle coordinates, relative to the right shoulder, were generally consistent across the six directions within each of the four hand location conditions (Table 1). The reach distances during the trial (ie. resultant distance between the shoulder and knuckle) also remained consistently close to the target of 80% of arm reach (79.3 ± 7.0%) across all combinations of 24 conditions and 15 participants (n = 360) and the area within the four locations was ~0.12 m^2. Most moment arms to the shoulder ranged from 0.36 to 0.52 m but, for the anterior/posterior forces with the arm in line with the shoulder (90°), they were 0.26 m near umbilical height and as low as 0.17 m near eye height (Table 2).

3.2. Joint axis strength

The average ratio of our mean measured JAS values versus the Stobbe JAS values was 1.20 ± 0.21, ranging from 0.88 (lateral) to 1.61 (forward) (Table 2). The rank order of both the elbow and shoulder JAS magnitudes were the same for the measured and Stobbe values. As noted above, the 3DSSPP v7.1.3 female elbow and shoulder strengths were almost identical to those from "All females" in Stobbe (1982) except for lateral humeral JAS.

Table 1

Summary of the mean and standard deviation of the lateral/medial (Lat/Med), anterior/posterior (Ant/Post) and superior/inferior (Sup/Inf) coordinates of the knuckle of the right hand and the superior/inferior coordinate of the elbow, with respect to the shoulder, for the four hand location conditions evaluated in 3DSSPP. The perpendicular moment arms of the three LAS force axes to the shoulder joint are also shown for each hand location. All values pooled across the 6 directions and 15 participants (n = 90) for each of the four hand locations (m).

	Height	Angle	Lat/ Med (x)	Ant/ Post (y)	Sup/Inf (z)	Elbow (z)
Mean	~Eye	~45°	0.34	0.37	0.14	0.07
		~90°	0.07	0.49	0.16	0.08
	~Umbilical	~45°	0.30	0.26	−0.25	−0.20
		~90°	0.04	0.41	−0.26	−0.25
St. Dev.	~Eye	~45°	0.05	0.04	0.04	0.04
		~90°	0.07	0.06	0.08	0.07
	~Umbilical	~45°	0.04	0.03	0.04	0.03
		~90°	0.03	0.04	0.04	0.03
Mom.Arm (Shld)	~Eye	~45°	0.39	0.36	0.50	
		~90°	0.52	0.17	0.50	
	~Umbilical	~45°	0.36	0.39	0.40	
		~90°	0.49	0.26	0.42	

3.3. Measured vs 3DSSPP estimates of female linear arm strength

Individual measured LAS values and those estimated with 3DSSPP are presented for all 24 conditions for each participant and pooled across participants within each condition (Fig. 4, Table B1). With the measured strength, the mean LAS values ranged from 74.4 ± 17.1 N (lateral direction, eye height, 90°) to 213.2 ± 43.3 N (anterior, umbilical, 90°). With the strengths estimated with 3DSSPP, the mean LAS values ranged from 39.7 ± 8.8 N (superior, eye, 45°) to 236.9 ± 106.9 N (anterior, eye, 90°).

Across all 360 comparisons of female one-armed 50th percentile LAS values, the 3DSSPP errors ranged from underpredicting by 135.2 N (participant 3, anterior, umbilical, 90°) to overpredicting by 294.7 N (participant 5, anterior, eye, 90°), respectively (Table B1). The mean absolute and relative errors were −6.7 N (ranging from −85.2 to +69.9 N) and −2.5% (ranging from −54.4 to 54.1%), respectively. The RMS absolute and relative errors were 56.0 N (ranging from 17.6 to 116.6 N) and 40.4% (ranging from 15.0 to 75.6%), respectively. Only 29.2% (ranging from 0.0% to 57.2%) of the variance in the actual measured LAS was explained by the 3DSSPP estimates of LAS. The explained variance within participants, across the 24 conditions, ranged from 10.4% to 54.1% (Table B1). Even when using only the mean measured and 3DSSPP LAS values, pooled across the 15 participants for each of the 24 conditions, the mean error remained at −6.7 N, the absolute and percent RMS errors were 39.5 N and 28.6%, respectively, and the explained variance was only 42.6%. When using a manikin with our average participant mass and stature, and the default 3DSSPP strengths, the mean error was −21.6 N, the absolute and percent RMS errors were 38.7 N and 25.7%, respectively, and the explained variance was even lower at 33.9% (n = 24).

When errors were pooled within the four hand locations, eye height with the arm rotated 90° was the only location that tended to overestimate LAS and had the highest RMS errors (Fig. 5). When pooled within the six directions, superior and posterior had the highest average underestimates (−50.3 N) and overestimates (+26.9 N), respectively. The directions with the largest RMS errors were (1) anterior, (2) posterior and (3) superior (Fig. 5).

It is interesting to note that, replacing 3DSSPP with just always guessing 135.5 N (the overall mean measured LAS) would have resulted in an RMS error of 47.3 N (n = 360), which is 15.5% lower than the 56.0

Table 2
Summary of mean participant strengths, Stobbe (1982) strengths and 3DSSPP v7.1.3 reference strengths in the same postures as those tested by Stobbe. The ratios of the measured divided by Stobbe strengths are shown for each axis direction. All values are in Nm.

		Mean (Nm)			Measured / Stobbe	St. Dev. (Nm)		
		Measured	Stobbe	3DSSPP		Measured	Stobbe	3DSSPP
Elbow	Extension	34.4	25.6	25.4	1.34	5.5	8.2	8.2
	Flexion	43.1	40.8	40.8	1.06	8.0	10.7	10.7
Shoulder	Medial	25.0	21.4	21.5	1.17	6.3	8.0	8.0
	Lateral	17.5	19.9	30.6	0.88	3.0	5.2	8.0
	Backward	39.9	34.1	34.1	1.17	7.6	10.8	10.8
	Forward	63.0	39.1	39.1	1.61	16.1	13.3	13.3
	Adduction	42.1	34.9	34.8	1.21	12.6	13.3	13.3
	Abduction	42.5	36.9	36.9	1.15	11.5	9.7	9.7

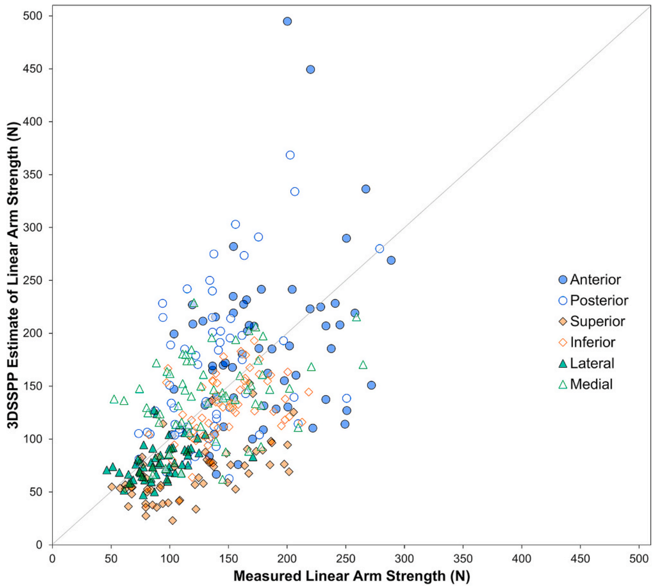

Fig. 4. All measured female one-armed LAS values (x axis) are plotted against those estimated with 3DSSPP v7.1.3 (y axis) (n = 360). Different markers indicate the six directions tested. Markers above and below the diagonal line indicate over and under predictions by 3DSSPP, respectively.

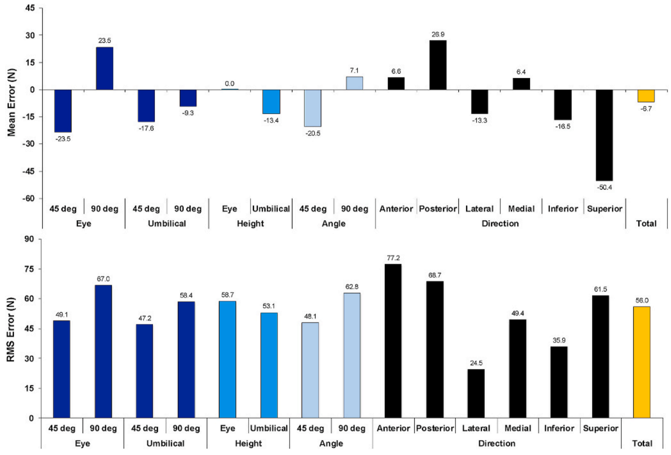

Fig. 5. Summary of errors pooled within the four hand locations (n = 90), each height (n = 180), each angle (n = 180, each direction (n = 60) and across all comparisons (n = 360).

N found when using 3DSSPP (Table B1). Further, based on 500 hundred simulations of the 24 conditions (n = 1200), just randomly guessing at any value between 60 N (6.1 kg) and 210 N (21.4 kg) resulted in an overall RMS error (56.9 N) that was very similar to the 56.0 N observed with 3DSSPP, at least for the 24 combinations of hand location and force direction tested.

3.4. Limiting joints in 3DSSPP

For the conditions and participants evaluated, LAS was limited in 3DSSPP by humeral rotation strength 41.9% of the time, followed by shoulder forward/backward (30.6%), elbow (15.0%) and shoulder abduction/adduction strength (12.5%). The least and most limiting axis directions were elbow flexion (2.2%) and lateral humeral (30.0%), respectively. For the 30% of cases where the lateral humeral axis direction was limiting, 3DSSPP tended to underestimate strength the most (by 42.0 N) even though the reference strength for this direction is the only one that is different (ie. 53% higher) than Stobbe (1982). If the Stobbe (1982) value had actually been used as the reference strength, lateral humeral would have likely been the limiting direction for a larger number of conditions and resulted in an even greater mean difference than the −40 N observed for lateral, and the −6.7 N observed overall. When the horizontal forward shoulder strength was limiting, it overestimated LAS the most, with a mean error of +34.9 N.

4. Discussion

Arm strength demands are a prevalent contributor to WSMD risk and digital human model software has been used for decades to evaluate the percent capable of the strength demands at multiple joints, with the shoulder or elbow joint often being the limiting factor. In this study, we compared empirically measured female linear arm strengths with those estimated by 3DSSPP, a popular software package with ergonomists. To ensure a direct comparison, we customized 3DSSPP v7.1.3 with the body mass, segment lengths, measured postures and joint angle strengths of each participant to ensure the truest test of the assumptions and calculations used to estimate linear arm strength based on posture and joint axis strengths.

The most important finding of this study is that the calculations made in 3DSSPP do not appear to accurately reflect the measured female linear arm strength capabilities for the 24 conditions evaluated. The RMS errors were very large at 56.0 N (5.7 kg) and 40.4%, and 3DSSPP explained only 29.2% of the variance in the measured linear arm strengths. In fact, simply guessing an LAS of 135.5 N every time would result in substantially lower errors than using 3DSSPP, at least for the 24 conditions tested. The largest RMS errors were with the anterior, posterior and superior directions, which are likely be the directions most commonly assessed with ergonomics software.

There are two major assumptions made by 3DSSPP, for the prediction of shoulder strength, that may have contributed to these large errors. First, for the two directions about each of the three axes, posture-based corrections are made to the reference strength estimates using the input of some combination of the rotations about the four axes - but 3DSSPP assumes that there are no interactions between the effects of orthogonal rotations. For example, the effect of changing vertical shoulder angle is assumed to be the same whether the rotation is in the coronal plane (ie. abduction where horizontal angle = 0°) or sagittal plane (ie. flexion where horizontal angle = 90°). 3DSSPP's second important assumption is that there is complete independence of the strengths about the three shoulder axes, as if torques are being generated by three separate motors, and this can result in overestimates of resultant strength. As stated by Garg and Chaffin (1975) "*it is assumed that the strength of a particular muscle group is not dependent on the level of loading on adjacent articulations*". For example, if 3DSSPP determined the average female lateral humeral, backward and adduction strengths to be 19.9, 41.1 and 37.0 Nm, respectively, it is possible that it would allow the torque demand to be equal to their resultant torque of 58.8 Nm. This would be 59% higher than the largest strength about any of the axes and 80% above the average of the three. This assumption has been proven to be invalid for efforts causing moments about the 3DSSPP abduction/adduction and forward/backward axes (Hodder et al., 2016; Makhsous et al., 1999).

With regards to the joint angle strengths, our JAS values were an average of ~20% higher than those in Stobbe (1982) and used in 3DSSPP (Table 2). This may be due to the younger average age in the current study (24.0 years) compared to Stobbe (31.3 years), but he did not present separate age means for males and females. It could also be due to random selection given the relatively small number of female participants here (15) and in Stobbe (32). There could have also been some secular changes since 1982.

Interestingly, when Stobbe's male and female lateral humeral "All Females" strength means and standard deviations (male: 34.9 ± 7.9 Nm, female: 19.9 ± 5.2 Nm) are compared to the corresponding values in 3DSSPP v7.1.3 with the same posture (male: 53.5 ± 12.1 Nm, female: 30.6 ± 8.0 Nm), the 3DSSPP values are exactly 1.53 times higher than both the means and both the standard deviations. Further, the lateral humeral reference strengths are the only elbow or shoulder values changed from v6 to v7 and, in 3DSPP v6, the means and standard deviations (male: 99.8 ± 22.6 Nm, female: 57.0 ± 14.9 Nm) were exactly 2.861 times higher than Stobbe for both the means and both the standard deviations. It is not clear why the 3DSSPP does not use Stobbe's lateral humeral strength means and standard deviations, nor is it clear why exact (but different) multiples of the Stobbe values were used in versions 6 and 7.

The high errors with 3DSSPP were not necessarily a surprise, given the relatively simplistic assumptions used to model the very complex shoulder, including the assumptions that there are no interacting effects of triaxial shoulder posture changes on JAS, and that JAS capabilities about one axis are completely independent of the demands about the other two axes. Also, since 3DSSPP bases percent capable values solely on the moment demand relative to the joint axis strength, its RMS errors tended to be inversely related to the moment arm from the force vector to the shoulder ($r = -0.69$). Across the 24 conditions, the highest RMS error of 116.6 N (11.9 kg) was observed for the condition with the smallest moment arm (0.143 m, anterior forces, near eye height with the hand rotated ~90° from lateral). In fact, theoretically, if the arm was fully extended and the hand was directly anterior to the shoulder, there would be no limit in 3DSSPP to anterior or posterior arm strengths because the moment arm to the wrist, elbow and shoulder would be zero and the force would cause a no moment demand in the software, no matter how high it was. This assumption was demonstrated to be invalid, likely due to the instability caused by high forces at the wrist, elbow and/or shoulder joints not accounted for in the 3DSSPP algorithms (Fewster and Potvin, 2014). The maximum error in the current study was observed when the anterior LAS estimated with 3DSSPP was 494.9 N while the measured anterior strength was only 200.2 N (participant 5, eye height, 90 deg) and this was most likely due to the very short moment arm to the shoulder (0.15 m) for that condition. The potential limitation of the advanced age of the Stobbe data, used as reference strengths for the elbow and shoulder in 3DSSPP, was irrelevant in the current study because we customized the software's JAS values to those measured directly from each individual participant.

Compared to other validation studies, the mean and RMS errors of −6.7 N and 56.0 N, respectively, were lower than the −45.2 N and 140.3 N observed by Garg and Chaffin (1975), likely because they did not have participant strength data to customize their LAS estimates and because they only evaluated males. The mean percent errors of −2.5% were similar to the −3% from Chaffin et al. (1987) but the explained variance of 29.2% was much less than their 50%. Finally, the RMS error of 56.0 N was more than double the 25 N found by Chaffin and Erig (1991).

There were some limitations in our study that should be addressed. We only collected data from female participants, because the 25th percentile female is most often the basis for strength thresholds in ergonomics (Waters et al., 1993), and we only studied 4 hand locations but the were in a range common to occupational exertions. The electromagnetic system used to estimate joint locations was not likely as accurate as using an optical system with multiple markers on each segment. However, we believe that the estimated joint centers were close to the actual values and that the 3DSSPP simulations would not have been systematically sensitive to small errors in joint locations and angles. The study was mainly focused on the prediction of linear arm strength based on elbow and shoulder strengths, so the wrist was eliminated as a limiting factor. Wrist and forearm strength measures are complex and were not feasible in this study, so we ensured that the collection of JAS data was designed to minimize the moment demands on the wrist and forearm. We did not allow participants to maximize LAS forces by applying resultant forces in a direction that deviated much from the intended direction. Most occupational tasks require forces primarily in the intended direction to avoid off axis motions if not constrained, or damage to parts if motions are constrained, so we required the force vector in the intended force direction to be at least 90% of the resultant. Finally, we only tested four hand locations, so generalizations of these results to all hand locations should be made with some caution.

5. Conclusions

This study performed a direct comparison between empirically measured female linear arm strengths and those estimated with the 3D Static Strength Prediction Program's (3DSSPP) algorithms to estimate linear arm strength. The analysis incorporated specific segment lengths, body masses, arm postures and elbow and shoulder joint axis strengths to create individualized, best-case scenario strength comparisons. In spite of efforts to customize the software to each participant, the errors in arm strength values from 3DSSPP were very high and were poorly correlated with measured strengths. In fact, just randomly guessing at a LAS value between 60 and 210 N, or always using the mean of 135.5 N, resulted in similar RMS errors as using 3DSSPP for the four hand locations and 6 directions evaluated. These results seriously question the accuracy of 3DSSPP for the conditions tested, and possibly other digital human model software packages that use a similar approach, to estimate female linear arm strengths and percent capable values, likely due to the overly reductive assumptions made to estimate triaxial shoulder strength.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Summary of 3DSSPP Linear Arm Strength Calculations and Validation Studies

Coordinate System and Joint Angle

All postures included an upright trunk and a coordinate system where +x is lateral to the right, +y is anterior and +z is superior. Elbow extension is defined as the angle between the upper arm (shoulder to elbow) and forearm (elbow to wrist), with full extension being 180°. The shoulder vertical angle is defined as the angle between the upper arm and a vertical line dropping from the shoulder parallel to the spine and is 0° when the upper arm is in the neutral posture (at the side) and 90° when the upper arm is parallel to the ground (eg. flexed or abducted 90°). The shoulder horizontal angle is defined as the angle between the upper arm and the lateral axis drawn between the two shoulders, when viewed from above. This angle is 0° when the upper arm is directly out to the side, in the coronal plane, negative when rotated behind, and 90° when rotated around and parallel to the sagittal plane. Shoulder humeral rotation is defined as the rotation of the plane defined by the shoulder, elbow and wrist with the perpendicular to the plane defined by the two shoulders and the lumber L5/S1 joint (ie. the sagittal plane in neutral standing).

Joint Strength Demand

Resultant joint moment demands on the elbow and shoulder are calculated using a linked-segment modelling approach with inputs of body mass and stature, joint location, and hand force magnitudes and directions. Elbow flexion and extension strength demands are calculated with the reaction moment about the elbow flexion/extension axis of each arm. The shoulder resultant moment demand is partitioned into reaction moments acting about the (1) humeral axis (along the forearm), (2) abduction/adduction axis defined as the line perpendicular to the projection of the humeral axis on the xy plane (transverse plane in upright standing) and (3) "forward/backward" axis defined as being directed perpendicular to the humeral and abduction/adduction axes. Humeral muscle actions are assumed to cause rotations about the upper arm towards the medial or lateral sides. Abduction muscle actions are assumed to cause rotations away from the trunk (eg. abduction in the coronal plane and flexion in the sagittal plane) and adduction muscle actions cause rotations towards the trunk (eg. adduction in the coronal plane and extension in the sagittal plane). Forward/backward muscle actions are assumed to rotate the upper arm about an axis through the shoulder that is parallel to the long axis of the trunk, with forward being toward the sagittal plane and backward being toward the coronal plane.

Joint Axis Strengths and Percent Capable Values

Elbow and shoulder reference strength 50th percentile and standard deviation values are based on Stobbe (1982), for most axis directions, with corrections for elbow and shoulder joint angles according to Schanne (1972) and possibly Clarke (1966). When a female mannikin is postured in 3DSSPP v7.1.3, to match the experimental postures described in Stobbe (1982, pages 268 to 291), its reference strength 50th percentile and standard deviation values were confirmed to be exactly the same as the Stobbe "All Females" table "Mean" and "SD" values for 7 of 8 axis directions. The only exception was the lateral humeral direction where Stobbe's measured strength was 19.9 ± 5.2 Nm, but the corresponding 3DSSPP v7.1.3 reference values was 30.6 ± 8.0 Nm (Table 2). Based on a sensitivity analysis, it appears that 3DSSPP corrects the following reference strengths based on the independent effects of the following rotations: elbow flexion and extension (elbow & shoulder vertical angles), shoulder forward (elbow, shoulder vertical & horizontal angles), backward (shoulder vertical & horizontal angles), abduction (elbow, shoulder vertical & humeral angles), adduction (shoulder vertical & horizontal angles), and both lateral and medial humeral (shoulder horizontal & humeral angles).

For both the right and left arms, percent capable values for the one elbow strength axis and the three shoulder strength axes are calculated based on the moment demand and the posture-corrected 50th percentile and standard deviation values, assuming a normal distribution. The force on the hands can be increased until the percent capable drops below its threshold (eg. 75 percent capable female) for one of the axes of interest. As noted, in our study, we made every effort to eliminate the wrist and forearm strengths as potentially limiting for LAS, but 3DSSPP would otherwise consider the wrist, along with the elbow and shoulder, when determining the LAS value.

Linear Arm Strength Model Validation Studies

Garg and Chaffin (1975) were the first to fully describe the model used in 3DSSPP to predict 3D static upper extremity strength. They compared LAS values, estimated with their model, to those studied by Thordsen et al. (1972) with 71 male subjects performing 37 one-armed exertion conditions, including 9 directions (anterior, posterior, superior, inferior, lateral, medial, lateral/posterior, medial/posterior, and anterior/medial) and up to 6 interfaces (stick, vertical throttle, horizontal throttle, panel, hatch and collective). The authors noted that they were not able to tune the model to even the average joint strengths of the experimental group, let alone the individual participant strengths. Instead, they assumed strength was proportional to body weight, but acknowledge that the two variables are only weakly correlated. In addition, forearm and wrist strength limitations were not considered, and it was not possible to estimate the actual postures adopted, or the off-axis forces during exertions. The authors did note that there were 8 conditions with significant off-axis forces, so those were removed from our analysis of the mean results in their Table 7. With the remaining 29 conditions, the mean error was −45.2 N, the RMS error was 140.2 N (>30 lbs) and the mean and RMS of the percent differences were −11.9% and 43.2%, respectively. The authors concluded that "*on a population basis, instead of using direct predictions from the model, empirically modified forces should be used for the present until a better strength model of the shoulder in particular is developed*" and finished by stating "*Certainly much more basic development is necessary before biomechanical strength models can be used to simulate many of the working conditions encountered in industry*". However, with regards to elbow and shoulder strength estimates made by 3DSSPP, we are aware of no fundamental improvements or changes in the software from the approach described in 1975, and it does not appear that there has been an incorporation of any empirical data more recent than that from the unpublished dissertation of Stobbe (1982).

Chaffin et al. (1987) compared the measured strengths of Rohmert (1966) from two force directions (superior and inferior) at 12 hand locations in the sagittal plane. The model explained only 50% of the variance in the measured LAS, but the average percent error was only −3%. However, their validation study was limited by not including forearm and wrist strength limitations in the model, not accounting for the potential role of balance in limiting force outputs, and the inclusion of a low number of only male participants (n = 5) with unknown joint strengths.

Chaffin and Erig (1991) compared their LAS model with measured strengths from Warwick et al. (1980) for 29 males. Based on their Figure 7, the approximate mean error was +13.6 N, and the RMS error was 25 N. However, it was not possible to delineate which of the ~81.1% of conditions were limited by the elbow or shoulder and, again, forearm and wrist strength were not considered in the model at that time, though it was subsequently added to 3DSSPP v6 in 2008.

Appendix B

Table B.1

Summary of the means and standard deviations of the female, linear arm strengths measured directly and estimated with 3DSSPP, the mean and RMS errors as absolute forces (N) and relative values (%), and the explained variance (r^2) for each of the 24 conditions (n = 15). Overall values in the last row are pooled across all 360 comparisons.

			Mean (N)		St. Dev. (N)		Mean Error		RMS Error		r^2
Height	Angle	Direction	Measured	3DSSPP	Measured	3DSSPP	N	%	N	%	
~Eye	**~45 deg**	**Anterior**	169.6	190.9	42.6	61.1	21.3	15.8%	56.4	40%	25%
		Posterior	133.0	106.9	41.2	21.7	−26.1	−13.9%	48.0	31%	6%
		Superior	88.8	39.7	15.9	8.8	−49.1	−53.7%	52.7	55%	5%
		Inferior	145.4	111.6	31.2	20.6	−33.8	−21.4%	44.2	27%	17%
		Lateral	113.2	93.2	20.6	14.4	−20.0	−15.0%	33.0	26%	3%
		Medial	150.6	117.4	33.2	33.5	−33.2	−18.1%	56.0	37%	0%
	~90 deg	**Anterior**	189.7	236.9	50.1	106.9	47.2	30.7%	116.6	62%	3%
		Posterior	133.9	203.8	33.2	70.3	69.9	51.9%	85.1	65%	57%
		Superior	76.1	66.3	15.1	17.3	−9.8	−12.1%	17.6	20%	33%
		Inferior	141.3	129.9	42.7	27.5	−11.3	−2.0%	42.8	31%	10%
		Lateral	74.4	74.9	17.1	17.5	0.6	4.4%	19.3	27%	11%
		Medial	93.3	138.0	21.9	43.2	44.7	54.1%	59.8	76%	12%
~Umbilical	**~45 deg**	**Anterior**	149.9	172.9	26.4	42.3	23.0	15.4%	37.1	27%	50%
		Posterior	120.1	115.7	40.8	25.2	−4.4	2.9%	38.8	29%	12%
		Superior	155.5	70.2	29.8	14.0	−85.3	−54.4%	88.4	55%	37%
		Inferior	157.0	152.8	23.2	22.2	−4.1	−1.5%	25.0	15%	14%
		Lateral	96.1	76.6	15.1	13.3	−19.5	−19.5%	23.4	23%	30%
		Medial	184.1	169.0	35.7	28.3	−15.1	−6.4%	38.8	19%	12%
	~90 deg	**Anterior**	213.2	148.1	43.3	59.9	−65.1	−31.9%	75.5	36%	56%
		Posterior	155.9	224.3	45.5	59.0	68.4	50.8%	88.6	66%	16%
		Superior	157.0	99.8	28.3	27.6	−57.2	−35.5%	65.1	40%	11%
		Inferior	154.6	137.9	17.5	22.3	−16.7	−10.4%	27.4	17%	15%
		Lateral	82.5	68.1	10.1	11.8	−14.5	−16.8%	19.7	22%	5%
		Medial	117.0	146.3	14.6	28.6	29.2	25.8%	39.3	34%	12%
Overall			**135.5**	**128.8**			**−6.7**	**−2.5%**	**56.0**	**40.4%**	**29.2%**

References

Bernard, B.P., 1997. Musculoskeletal Disorders and Workplace Factors. U.S. Department of Health and Human Services, Cincinnati, Ohio.

Chaffin, D.B., Erig, M., 1991. Three dimensional biomechanical static strength prediction model sensitivity to postural and anthropometric inaccuracies. IIE Trans. 23, 215–227.

Chaffin, D.B., Freivalds, A., Evans, S.M., 1987. On the validity of an isometric biomechanical model of worker strengths. IIE Trans. 19, 280–288.

Clarke, H.H., 1966. Muscle Strength and Endurance in Man. Prentice-Hall, Englewood Cliffs, NJ.

Fewster, K.M., Potvin, J.R., 2014. Maximum forces and joint stability implications during in-line arm pushes. Theor. Issues Ergon. Sci. 16, 1–12.

Garg, A., Chaffin, D.B., 1975. A biomechanical computerized simulation of human strength. AIIE Trans. 7, 1–15.

Hodder, J.N., La Delfa, N.J., Potvin, J.R., 2016. Testing the assumption in ergonomics software that overall shoulder strength can be accurately calculated by treating orthopedic axes as independent. J. Electromyogr. Kinesiol. 29, 50–54.

Keyserling, W.M., 2000. Workplace risk factors and occupational musculoskeletal disorders, Part 1: a review of biomechanical and psychophysical research on risk factors associated with low-back pain. Am. Ind. Hyg. Assoc. J. 61, 39–50.

La Delfa, N.J., Freeman, C.C., Petruzzi, C., Potvin, J.R., 2014. Equations to predict female manual arm strength based on hand location relative to the shoulder. Ergonomics 57, 254–261.

La Delfa, N.J., Potvin, J.R., 2017. The 'Arm Force Field' method to predict manual arm strength based on only hand location and force direction. Appl. Ergon. 59, 410–421.

La Delfa, N.J., Potvin, J.R., 2016. Multidirectional manual arm strength and its relationship with resultant shoulder moment and arm posture. Ergonomics 59, 1–12.

Makhsous, M., Högfors, C., Siemieński, A., Peterson, B., 1999. Total shoulder and relative muscle strength in the scapular plane. J. Biomech. 32, 1213–1220.

National_Safety_Council, 2020. Work Injuries and Illnesses by Part of Body. Injury Facts. https://injuryfacts.nsc.org/work/industry-incidence-rates/work-injuries-and-illnesses-by-part-of-body/. (Accessed 12 January 2020).

Nussbaum, M.A., Zhang, X., 2000. Heuristics for locating upper extremity joint centres from a reduced set of surface markers. Hum. Mov. Sci. 19, 797–816.

Rohmert, W., 1966. Maximalkräfte von Männern im Bewegungsraum der Arme und Beine. Westerdeutscher Verlag, Koln, Germany.

Schanne, F.J., 1972. Three-Dimensional Hand Force Capability Model for Seated Operator. PhD Thesis. University of Michigan, Ann Arbor, MI.

Stobbe, T.J., 1982. The Development of a Practical Strength Testing Program for Industry. PhD Thesis. University of Michigan, Ann Arbor, MI.

Thordsen, M.L., Droemer, K., Laubach, L.L., 1972. Human Force Exertions in Aircraft Control Locations. Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.

Waters, T.R., Putz-Anderson, V., Garg, A., Fine, L.J., 1993. Revised NIOSH equation for the design and evaluation of manual lifting tasks. Ergonomics 36, 749–776.

Yassi, A., 2000. Work-related musculoskeletal disorders. Curr. Opin. Rheumatol. 12, 124–130.