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In Vivo Pediatric Shoulder Muscle Volumes and Their Relationship to 3D Strength

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Abstract

In the pediatric shoulder, injury and pathology can disrupt the muscle force balance, resulting in severe functional losses. As little data exists pertaining to *in vivo* pediatric shoulder muscle function, musculoskeletal data are crucially needed to advance the treatment of pediatric shoulder pathology/injury. Therefore, the purpose of this study was to develop a pediatric database of *in vivo* volumes for the major shoulder muscles and correlate these volumes to maximum isometric flexion/extension, internal/external rotation, and abduction/adduction joint moments. A methodology was developed to derive 3D shoulder muscle volumes and to divide the deltoid into sub-units with unique torque producing capabilities, based on segmentation of three-dimensional magnetic resonance images. Eleven typically developing children/adolescents (4F/7M, 12.0±3.2years, 150.8±16.7cm, 49.2±16.4kg) participated. Correlation and regression analyses were used to evaluate the relationship between volume and maximum, voluntary, isometric joint torques. The deltoid demonstrated the largest (30.4±1.2%) and the supraspinatus the smallest (4.8±0.5%) percent of the total summed volume of all six muscles evaluated. The anterior and posterior deltoid sections were 43.4±3.9% and 56.6±3.9% of the total deltoid volume. The percent volumes were highly consistent across subjects. Individual muscle volumes demonstrated

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CONFLICT OF INTEREST

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moderate-high correlations with torque values (0.70–0.94, $p < 0.001$). This study presents a comprehensive database documenting normative pediatric shoulder muscle volume. Using these data a clear relationship between shoulder volume and the torques they produce was established in all three rotational degrees-of-freedom. This study furthers the understanding of shoulder muscle function and serves as a foundation for evaluating shoulder injury/pathology in the pediatric/adolescent population.

Keywords

Torque; MRI; Children; Reliability; Rotator Cuff; Injury

INTRODUCTION

Shoulder stability and function are predominantly maintained by a balance of muscle forces (Ackland and Pandey, 2011; Boettcher et al., 2010; Otis et al., 1994). As such, congenital conditions (e.g., brachial plexus palsy (Kozin et al., 2010) and cerebral palsy (Abel et al., 2003; Brochard et al., 2012)) can cause muscle imbalances and skeletal deformities, resulting in functional losses in both the pediatric and adult populations. Sports related injuries, which have been viewed as primarily adult issues, are now becoming prominent in pediatric populations as participation in high-level competitive sports is occurring at earlier ages (Davis, 2010; Emery, 2006). Unfortunately, much of the existing knowledge regarding shoulder function originates from adult cadaver and modeling studies. Since evidence suggests that children may not simply be scaled versions of adults (Neu et al., 2002; Tonson et al., 2008), *in vivo* pediatric shoulder musculoskeletal data are needed to enhance the understanding of typical shoulder function and improve the management and treatment of pediatric shoulder pathology/injury.

Although it is well accepted that an individual muscle's volume can predict its force generating capacity (Akagi et al., 2009; Blazevich et al., 2009; Fukunaga et al., 2001), establishing this relationship for the shoulder presents unique challenges. Specifically, the largest shoulder muscle (deltoid) has multiple lines of action, which enables it to generate torques on humerus in opposite directions (Ackland and Pandey, 2011; Brown et al., 2007; Kuechle et al., 2000). Specifically, the anterior deltoid segments produce humeral flexion torque, while the posterior segments produce humeral extension torque. Likewise, but to a lesser degree, the deltoid is capable of ab/adduction and internal/external rotation torques. Thus, it is difficult to relate the volume of the deltoid to its ability to generate a torque in a specific direction. This has resulted in a paucity of data with regards to the shoulder muscle volume-torque relationship. To evaluate the full three-dimensional (3D) muscle volume-torque relationship an *in vivo* methodology is needed for separating the deltoid into sub-units with non-antagonist torque producing capabilities. Currently, the volume-torque relationship has been evaluated for only one of the three rotational degrees of freedom (DOF_R), ab/adduction (Audenaert et al., 2009; Holzbaur et al., 2007; Vidt et al., 2012). The pediatric shoulder muscle volume-torque relationship has not been quantified. Rather, individual shoulder muscle cross-sectional areas have been used to evaluate hypertrophy

with training (Pitcher et al., 2012) and functional losses with pathological atrophy (Poyhia et al., 2005)..

Therefore, the primary purpose of this study was to establish a normative pediatric database of shoulder muscle volume and its distribution, spanning a range of ages, sizes, and genders. The deltoid, pectoralis major, teres minor/infraspinatus, teres major/lattisimus dorsi, supraspinatus, and subscapularis were evaluated. The secondary purpose was to associate shoulder muscle volumes with the maximum voluntary isometric joint moments they produce in all three DOF_R. To accomplish these two purposes, an *in vivo* methodology for splitting the deltoid into functional sub-units was developed. The inter-rater reliability of obtaining pediatric muscle volumes and creating deltoid sub-units was evaluated.

METHODS

Fourteen typically developing children/adolescents were recruited for this IRB (National Institute of Child Health and Human Development, intramural) approved study. A legal guardian or subject over 18 years of age provided written consent. Additionally, each subject under 18 years of age provided written assent. A pediatric physiatrist performed a history and physical. Potential subjects with active or historical upper limb pathology/injury or known contraindications to MR imaging were removed from the study. Three children declined MR imaging after enrollment and withdrew, leaving a cohort of seven males and four females (Table 1).

MR acquisition

Each participant was given time to become accustomed to the scanner. The subject was placed supine on the plinth of a 3-Tesla MR scanner (Verio; Siemens, Germany). To optimize the signal- and contrast-to-noise ratios, the dominant shoulder was positioned at the MR isocenter. In addition, standard cardiac flex coils were positioned anterior, posterior, and lateral to the shoulder. The arm was placed as close to anatomical position as possible with the forearm pronated for comfort. Sandbags were placed alongside the arm and a large supportive strap was gently secured around the coils and chest. A T1-gradient recalled echo sequence was acquired for the dominant shoulder. With the exception of the in-plane field of view, all scanning parameters were held constant across subjects (416×312×192 pixels, slice thickness 1.2mm, TR=16.6msec, TE=5.1msec, imaging time=4min 22sec). This slight variation in the in-plane resolution across subjects (0.55mm x0.55mm – 0.63mm x0.63mm) enabled higher resolution for smaller subjects.

MR image processing

Individual muscle volumes were quantified from 3D muscle models, derived by segmenting the MR data (Figure 1) in MIPAV (NIH, Bethesda, MD). Segmentation guidelines were established in a preliminary dataset. An image magnification factor of six was used to achieve greater precision. Muscle segmentations began and ended with at least five consecutive MR image slices. To maximize efficiency without sacrificing accuracy, every slice was not segmented in the mid-belly of the muscles. For the shortest muscle (supraspinatus), every other slice was segmented in the mid-belly. For the mid-length

muscles (infraspinatus/teres minor, subscapularis, and teres major) every fourth slice was segmented in the mid-belly. For the longest muscles (deltoid and pectoralis major) every sixth slice was segmented in the mid-belly. Segmentation was guided by tracking minor changes in area through the “skipped” slices and by visualizing muscle fascial planes, origins, and insertions in a tri-planar view (MIPAV). Segmentation propagation direction was inferior to superior. The segmentation process created a point cloud delineating the outer edge of the muscle (Figure 1). This point cloud was imported into Geomagic (Research Triangle Park, NC) and a surface was wrapped to the points without smoothing filters. Any errors in the wrapping (e.g., holes in the surfaces, overlapping surfaces areas, etc.) were manually corrected. The final muscle volume was recorded. Each muscle’s volume was also reported as a percent volume of the total summed volume of the six muscles measured.

The deltoid, pectoralis major (PM), supraspinatus, and subscapularis were segmented as individual muscles. The infraspinatus and teres minor were segmented as one muscle (I-tm) because they have analogous functions and the fascial boundaries between them are often indistinct (Lehtinen et al., 2003; Portney and Watkins, 2009; Talbert et al., 2011; Van Geleijn Vitringa et al., 2011). Using a similar rationale, the teres major (TM) was segmented assuming its distal border was at the level of the most distal scapula point. In doing so, a small portion of the latissimus dorsi was included in the TM volume. The latissimus dorsi was not separately segmented, as it was not fully captured in taller subjects. The research team was blinded to the subject’s demographics throughout the analysis phase.

Assigning muscles to functional groups

Muscle function was categorized (Table 2) based on moment arm data from studies that used an identical testing position (Brown et al., 2007; Kuechle et al., 1997; Kuechle et al., 2000). Muscles with moment arms greater than 3mm in a selected torque direction were defined as contributors to that direction. This was a qualitative decision based on the fact that a 4mm moment arm was ~10% of the largest moment arm (Table 2). Although the TM is often reported as an adductor, currently it was not categorized as such, as it has an adductor moment arm less than 3mm with the shoulder flexed to 90° (Kuechle et al., 1997).

Splitting the deltoid into functional compartments

To quantify the deltoid volume and associate it with the primary torques it produces, the deltoid was split into two segments (Figure 2), based on the seven functionally independent segments defined by Brown and colleagues (2007). Neither a full seven-way, nor a three-way split (Klepps et al., 2004; Lorne et al., 2001), was used based on the results of a preliminary study, which demonstrated that it was not feasible to reliably identify the fascial planes for these splits in the MR images. Attempting to do so resulted in inconsistent segmental volumes across subjects that did not match well with the previous data (Brown et al., 2007; Peterson and Rayan, 2011). The anterior segment, which combined the anterior three sections of the seven-segment model (Figure 2), was considered a flexor; whereas the posterior section, which combined the posterior four sections (Figure 2) was considered an extensor. The entire deltoid was considered an abductor, as only the smallest segment of the seven-segment deltoid model (closest to the spinal column) produces adduction (Brown et

al., 2007). Although minor torques of the deltoid, internal and external rotation were assigned to the anterior and posterior deltoid, respectively (Kuechle et al., 2000).

The deltoid was divided using a 2D slice plane, defined by three points (S1, S2, and D; Figure 3). S1 and S2 were the medial and lateral borders of the fascial plane between the deltoid segments at the level of the mid-acromioclavicular joint (Wickham and Brown, 1998). To ensure that the correct border had been defined, the four intramuscular tendons posterior to the bicipital groove (Sakoma et al., 2011) were identified in an image at the superior aspect of the humeral head. The third most posterior tendon (AP tendon, Figure 3) represented the border between the anterior and posterior segments. If this tendon did not communicate with the fascial plane defined by points S1 and S2, the images were re-evaluated until agreement was reached. Point D was defined as the center of the fascial plane dividing the deltoid segments just proximal to the posterior deltoid's humeral insertion (segments D3 and D5, Figures 2 and 3). As a final check, the separation of the deltoid segments was visualized on a sagittal reconstruction of the 3D axial image set.

Reliability of Muscle Volumes

To test the inter-rater reliability, two investigators independently analyzed the volumes for the I-tm and supraspinatus, along with the anterior, posterior, and total deltoid. These muscles were chosen to represent a variety of shapes, sizes, depths, and functions. Intra-class correlation coefficients (ICCs), using a two-way mixed effects model, were computed. The muscle volumes were acquired, using the identical protocol, for the unimpaired, dominant arm of ten children/adolescents (six boys and four girls) with unilateral brachial plexus palsy. This cohort had similar demographics (age= 12.1 ± 3.3 years, height= 157.8 ± 20.9 cm, and weight= 51.5 ± 17.3 kg) to the typically developing children/adolescents of the main study.

Maximum Isometric Torque Measures

Identical to a previous study (Brochard et al., in press) maximum voluntary isometric joint torques ("strength") were measured by a physician for all three DOF_R using a hand-held dynamometer (Jtech Commander powertrack II). Subjects were assessed in six functional directions. Testing position, testing order (flexion, abduction, external rotation, internal rotation, adduction, and extension), and verbal instructions were standardized. All torque measures were acquired with the subject lying on a plinth and the shoulder in the anatomic position, with one exception. To maximize reliability, max-adduction strength was measured with the subject prone and the humerus in 90° of flexion. For internal/external rotation assessments, a strap was used to stabilize the upper-arm against the body. Subjects first conducted a sub-maximal contraction as a practice/warm-up. Three trials of maximal voluntary isometric contractions were performed in each direction, while subjects were encouraged to push as hard as they could with the shoulder without moving or displacing the elbow from its rest position. Only trials lasting at least three seconds were accepted. Subjects rested ten seconds between trials and a minimum of one minute between different directions.

Statistics

The 3D volumes of the six muscles, along with the anterior and posterior deltoid volumes, were correlated (Pearson's) to the strength (SPSS ver19, IBM, Armonk, NY). A multivariate regression analysis was performed to determine if the combined volumes of a functional group (Table 2) could better predict the maximum isometric joint torques. A p-value < 0.05 was considered significant.

RESULTS

In this pediatric database, the largest total volume (summed volume of all six muscles) was three and a half times greater than the smallest (273.2 – 943.8 cm²). The deltoid demonstrated the largest percent volume of the six muscles segmented (Table 3, 30.4 ± 1.2%) and the supraspinatus demonstrated the smallest (Table 3, 4.7% ± 0.5%). The percent volumes were highly consistent across subjects, with coefficients of variation ranging from 0.038 (deltoid) to 0.107 (supraspinatus) and a correlation between each individual muscle and the total muscle volume ranging from 0.937 to 0.996 (Figure 4).

The anterior and posterior deltoid sections were 43.4±3.9% and 56.6±3.9% of the total deltoid volume (Table 3). If defined as a percent of the total shoulder muscle volume these deltoid sub-sections demonstrated consistency similar to all other muscles.

The individual muscle volumes were moderately to strongly correlated with maximum voluntary isometric joint torques (Table 2, max r-values for each torque direction ranged from 0.789–0.937 (p<0.001)). Therefore, 62–91% of the maximum isometric torque could be predicted from single muscle volumes. Using multivariate regression analyses improved the predictability for external rotation only (r²=0.94 p<0.001).

The maximum voluntary isometric joint torques were strongly correlated with each other. The torques in antagonistic directions (flexion/extension, internal/external, abduction/adduction) had correlation coefficients ranging from 0.866–0.951 (p<0.001). The correlation of each torque with the torques in orthogonal directions ranged from 0.844–0.966 (p<0.001).

The inter-rater reliability for generating muscle volumes was excellent (ICC = 0.993–0.999), well above the level required for “clinical relevance” (Portney and Watkins, 2009). The average inter-rater differences were -0.9±4.5cm³, 2.2±2.1cm³, and -1.0 ±2.3cm³ (-0.4%, 2.1%, and -2.8%) for the entire deltoid, infraspinatus, and supraspinatus. Quantifying the anterior and posterior deltoid segments demonstrated excellent inter-rater reliability (ICC = 0.970 and 0.989 p<0.001). The average inter-rater differences were -6.5±12.1cm³, and 6.0 ±9.8cm³ (-6.4% and 4.3%).

DISCUSSION

This study presents a comprehensive database documenting normative pediatric shoulder muscle volume. Using these data an association between muscle volume and strength was established in all three DOF_R. The methodology for reliably splitting the *in vivo* deltoid volume into subgroups with unique torque producing abilities is important for further research, as it simplifies the evaluation of a muscle with multiple actions. Fortunately, the

application of this methodology is not limited to pediatric data, but should be directly applicable to adult data as well. Thus, both the methodologies developed and the databases established within this study will likely advance the understanding of shoulder injury, pathology, and overuse by facilitating functional-based analyses in both the pediatric and adult populations.

Despite the diverse spectrum of ages and sizes, the muscle volume distribution remained consistent across individual subjects. Hence, this normative pediatric muscle database could be beneficial for estimating shoulder muscle volumes, particularly when such data are difficult to obtain. For example, acquiring MR data for children often requires anesthesia (Halliday and Kelleher, 2013; Usher and Kearney, 2003), yet such a risk is difficult to justify for research purposes. This database also provides a baseline to which atrophic (e.g., children with cerebral palsy or brachial plexus palsy) or hypertrophic (e.g., overuse) muscle volumes can be compared.

The relative distribution of shoulder muscles in children appears to be consistent with adults (Figure 5) with a few notable exceptions. In this pediatric cohort the deltoid occupies a relatively smaller, and the rotator cuff muscles (supraspinatus, subscapularis, and I-tm) a relatively larger, percentage of the shoulder muscle volume (Holzbaur et al., 2007; Peterson and Rayan, 2011; Vidt et al., 2012). The differences in muscle distribution, albeit small, between the current pediatric and previous adult cohorts, combined with the documented humeral shape changes during development (Edelson, 2000; Sheehan et al., in press) indicate that caution must be used when applying results from adult modeling and experimental studies to pediatric populations.

The concept that muscle volumes are predictive of maximum isometric torques was supported by the moderate to strong regression coefficients. The differences in regression coefficients across muscles of a functional group (Table 2) were quite small, a likely a result of the strong association between muscle volumes. The results expand upon the current knowledge of the *in vivo* relationship between shoulder muscle volume and strength by establishing these relationships for all cardinal planes. The inability to fully explain the variance in maximum voluntary isometric joint torques was anticipated, as numerous other factors (e.g., moment arm values, specific tension, fiber length, and pennation angles) also influence a muscle's ability to generate torque. As these parameters are most often derived from cadaveric studies, such data for the pediatric shoulder are unavailable. In addition, these parameters can vary across the muscles of the shoulder. Thus, the quantified volume-torque relationship defines the relationship between a single muscle's volume and the torque it can produce, which will likely be useful in evaluating the effects of muscle atrophy/hypertrophy in the production of torque. The conclusions of this study in no manner imply that the muscle volume alone can quantify differences in strength across different muscles (Ward et al., 2006; Zajac, 1992).

The abduction/adduction regression coefficients matched well with literature values (Audenaert et al., 2009; Vidt et al., 2012), but tended to be smaller. This difference may have arisen from the fact that the overall volume was fairly evenly distributed across genders in the current study (Figure 4), but in a past study (Vidt et al., 2012), the average female

volume was ~18 standard deviations less than the average male volume. This large difference in volume between the male and female populations likely create a correlation that was stronger for the entire population, but weaker within the sub-populations.

The fact that the multivariate regression analysis improved the prediction of only one (external rotation) of the six joint torques indicates that the relationship between individual muscle volumes and torque may be more relevant than the relationship between the summed muscle volumes within a functional group and its corresponding torque (Holzbaur et al., 2007). Performing a regression based on the summed volume assumes that the multiplicative coefficient for each muscle volume is a constant. This constant accounts for the moment arm, specific tension, and pennation angle of each muscle. There can be no expectation that it would be constant across muscles of a functional group. In addition, the colinearity amongst the volumes created a bias against improving the single regressions with a multivariate regression.

The cross-correlation between joint torques was expected as shoulder function requires a high level of dynamic interaction between co-contracting muscles. Thus, the shoulder's capacity to produce force in one direction is balanced by a reciprocal capacity to produce force in the opposite direction.

It is well accepted that the deltoid is functionally capable of producing moments on the humerus in opposing directions. Dividing the deltoid based on the seven-segment deltoid model (Brown et al., 2007) provided clear guidance for assigning extension, flexion, and abduction to the segments. Compared to these torques, the deltoid's ability to produce internal/external rotation is minor and these moment arms have only been reported based on three-segment models (Ackland et al., 2008; Otis et al., 1994). The anterior deltoid is an internal rotator, whereas the posterior deltoid is an external rotator, but the mid-deltoid has been reported as being both an internal (Ackland and Pandey, 2011) and external (Otis et al., 1994) rotator. As the seven-segment model can be converted to the commonly used three-segment model by combining segments (anterior= D1+D2, mid = D3+D4, and posterior= D5+D6+ D7, Figure 2), the current two-segment deltoid allocated a small portion of the mid-deltoid to the anterior and posterior segments, forming a compromise across past studies. A more realistic 3D curved plane defining the boundary between sections D3 and D4 was not used since identifying it in the mid-belly was difficult and time-consuming. In a preliminary dataset, a comparison of the segmental volumes derived using the 2D and 3D slice planes demonstrated little volumetric differences.

Although the current methodology deviated slightly from the three-segment deltoid model (Klepps et al., 2004; Lorne et al., 2001), it enabled the deltoid to be reliably divided into sub-units with unique torque producing abilities. This methodology is pivotal to establishing the *in vivo* volume-torque relationship for all three DOF_R. More importantly, it opens a rich path for research into injury, pathology, and hypertrophy in both pediatrics and adult populations. For example, in obstetrical brachial plexus palsy, external rotation and extension torque weakness have been documented (Kozin et al., 2010). Yet, the contribution of deltoid atrophy to this weakness may have been masked by a reliance on evaluating the entire deltoid (Hogendoorn et al., 2010; Van Geleijn Vitringa et al., 2011).

In this pediatric cohort, the anterior deltoid was a smaller percentage (43.4%) of the entire deltoid relative to the limited available adult cadaver data. For a single adult cadaver, the anterior-posterior deltoid split was 50.7%-49.2% (Wickham and Brown, 1998). For five adult cadavers it was approximately 46.5%–52.5% (Peterson and Rayan, 2011). This may indicate a differential development of the functional sub-units within the deltoid. To more fully explore this issue, future work is needed to establish *in vivo* adult segmental volumes.

This study confirms that the process of deriving muscle volumes from MR images in children/adolescents is as reliable as in adults, if not more so. The inter-rater reliability matched that of Tingart and colleagues (2003), but the average difference (−0.4%) was lower than the 4% reported for the intra-rater reliability of the deltoid (Holzbaur et al., 2007). The higher percent differences (6.4% and 4.3%) for the anterior and posterior deltoid segments arose primarily from a single subject with −40.2 and a 31.2cm³ difference in segment volumes between observers. Advancements in MR technology have provided higher resolution, stronger MR units (3-Tesla) with larger bores, allowing optimal subject placement and increased signal-to-noise ratios. This enabled the voxel resolution for the current study (0.36–0.48mm³) to be two times better than the data acquired by Tingart and colleagues (2003). Thus, the current accuracy is likely equivalent to or better than the 2–4% accuracy reported in this previous study.

While the present study is the largest and most comprehensive database documenting the relationship between pediatric shoulder muscle volume and strength, the cohort is still objectively small, and thus a limitation of the study. For this reason, the full individual dataset is provided so that future experimental and modeling studies can use the current data as a foundation. In the current pediatric database, it was not feasible to create a “gold standard” in which to evaluate the methodology for dividing the deltoid. Therefore, the exact accuracy remains unknown.

This study quantified 3D, *in vivo* shoulder muscle volumes and their association with strength in a normative pediatric population. The potential for asserting definitive conclusions with regards to shoulder muscle function, particularly differences between the pediatric and adult shoulder, is predicated on expanding the normative database quantitatively (i.e., additional subjects) and qualitatively (i.e., broader sample of characteristics). The current data provides a reference for clinicians and researchers investigating pediatric shoulder pathology. This information is useful in identifying muscle imbalances and tailoring interventions to specific muscles and functions.

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Figure 1. Segmentation

Left Column: Images 118 and 119 are ~18.4% and ~18.8% of the humeral length distal from the superior aspect of the humeral head. For this subject (same subject depicted in Figure 3) the images resolution is $0.6 \times 0.6 \times 1.2$ mm. In this location, the area of the pectoralis major, subscapularis, deltoid, and I-tm demonstrate minimal change between slices. As these images contain the superior aspect of the teres major, there is a rapid change in its area. For this reason every slice was segmented for at least five slices representing the origin and insertion of the muscle, but the segmentation was not done for every slice in the mid-belly of the muscle. **Top Right:** The segmentation generates an individual point cloud for each muscle (yellow: suprascapularis, red: I-tm, and blue: subscapularis). **Bottom Right:** A 3D surface was wrapped to the point cloud. After manual correction of any minor errors in the model, the volume was calculated. Note, the humerus is shown slightly transparent in order to highlight the scapula.

Figure 2. Deltoid Functional Divisions

Left: Previous studies have provided evidence that the deltoid is comprised of seven unique functional groups. Based on the quantification of moment arms, Brown and colleagues (2007) defined these segments as flexors-abductors (D1–D3), extensors-abductors (D4–D6), and extensor-adductors (D7). The internal-external rotation moment arms were not reported. The study of Sakoma and colleagues (2011) also supported this division into seven segments (defined as A1, A2, A3, M1, P1, P2, and P3, which roughly matched D1–D7). The origins of segments D6–D7, D3, and D1 are isolated to the scapular spine, the acromion process, and the clavicle, respectively. The origins of D4 and D2 span the acromion and either the spinal process or the clavicle. **Top Right:** The anterior (D1–D3) and posterior (D4–D7) segments were assigned to the flexion-internal rotation and the extension-external rotation functional groups, respectively. **Bottom Right:** The entire deltoid volume was considered an abductor since the volume of D7, which contributed to adduction, was negligible compared to the entire deltoid.

Figure 3. Defining the three points of the anterior-posterior deltoid slice plane

Both rows present two axial images whose locations are defined by the horizontal arrows extending to the center sagittal image. Similarly, the location of the central sagittal image is indicated on the right and left axial images using vertical arrows. Note ax1 and ax4 have both been enlarged and cropped for better visualization. **Top Row:** The proximal two points defining the 2D slice plane were defined in the axial image at the level of the acromioclavicular joint (ax1). To ensure that the fascial plane dividing the anterior and posterior deltoid (AP fascial plane) had been located, the intramuscular tendons (as defined by Sakoma and colleagues (2011)) were identified in an axial image at the superior aspect of the humeral head. The “AP tendon” marks the division between the anterior and posterior deltoid. This tendon was followed back to image ax1 to ensure that it communicated with the AP fascial plane. **Bottom Row:** Just superior to the distal insertion of the posterior deltoid, the AP fascial plane was identified and the center of this plane was the 3rd point. A 3D plane outlining the fascial plane could not be used because the fascial plane in the mid-belly of the deltoid was often indistinguishable, as can be seen in ax3.

Figure 4. Individual Muscle Volume Relative to Total Muscle Volume

All correlations had a p-value <0.001. The grey arrows mark the data from the female subjects. Abbreviations: PM –Pectoralis Major, Sub – Subscapularis, TM – Teres Major, Supra – Supraspinatus, Post. – Posterior, Ant. – Anterior, I-tm – Infraspinatus/Teres Minor.

Figure 5. Comparison of the Muscle Volume Distribution

The distribution was calculated based on only the muscles that overlapped between studies.

TOP: Comparison to past *in vivo* studies in young adults and elderly (Holzbaur et al., 2007; Vidt et al., 2012). **BOTTOM:** To past cadaver study (Peterson and Rayan, 2011). As Peterson and Rayan (2011) reported average masses, the percent volumes were based on the assumption that muscle density was constant across muscles. **Note:** The distributions are slightly different than those listed in Table 3 since the set of muscles used for the total volume was dependent on the data available in the previous studies. Although measured, the volume of the teres major was not included in the above figures because it was calculated differently than had been done previously. Abbreviations: PM –Pectoralis Major, Subscap – Subscapularis, Supraspin – Supraspinatus, I-tm – Infrapinatus/Teres Minor.

Table 1
Subject data. Top
Cohort demographic and anthropomorphic data. Abbreviations: BMI = body mass index; SD = standard deviation.

Subject	Gender	Dominant Arm	Age (years)	Height (cm)	Weight (kg)	BMI	Weight Category ^A
1	M	R	13.8	157.5	74.3	29.9	Obese
2	M	R	14.5	180.3	72.0	22.1	Normal
3	M	R	11.4	159.0	40.5	16	Normal
4	M	R	7.3	131.0	23.9	13.9	Normal
5	M	R	11.1	130.0	44.6	26.4	Obese
6	M	R	9.2	142.2	47.3	28.2	Obese
7	M	R	13.7	151.8	64.9	18.2	Under
8	F	R	8.7	127.0	26.3	23.4	Obese
9	F	R	10.8	152.4	45.5	16.3	Normal
10	F	R	18.7	165.1	49.5	19.6	Normal
11	F	L	12.4	162.6	53.1	20.1	Normal
Mean							21.3
SD							5.2

^ACenters for Disease Control categorization based on BMI

TABLE 2
Pearson Correlation Coefficients and Regression Values for Muscle Volume-Torque Relationship

Correlation and regression coefficients (columns 5 and 6) between the maximum isometric torque produced in specific directions (column 1) and the individual muscle volumes for selected muscles (column 2) are presented. Muscles identified as torque contributors to a given direction were labeled as primary, secondary, or minor (column 4). These categorizations were largely based on moment arms (column 3) from relevant studies, but other factors such as size and clinical knowledge were considered in assigning a role. Abbreviations: PM – Pectoralis Major, TM – Teres Major, I-tm – Infraspinatus/Teres Minor.

Torque Direction	Muscle	Moment Arm (mm)	Role	r-value	r ² -value
Flexion	Anterior Deltoid	15.9 ^a	Primary	0.885	0.784
	Supraspinatus	7 ^b	Primary	0.819	0.670
	PM	10 ^b	Primary	0.853	0.728
	I-tm	4 ^b	Minor	0.919	0.844
Extension	Posterior Deltoid	45.4 ^a	Primary	0.937	0.878
	TM	38 ^b	Primary	0.891	0.794
Abduction	Supraspinatus	19 ^b	Primary	0.701	0.492
	Total Deltoid	19.5 ^a	Primary	0.784	0.614
	I-tm	19 ^b	Secondary	0.806	0.649
Adduction	PM	21 ^b	Primary	0.772	0.596
	Subscapularis	8 ^b	Minor	0.832	0.693
Internal rotation	Subscapularis	22.5 ^c	Primary	0.750	0.562
	PM	20 ^c	Secondary	0.772	0.591
	Anterior Deltoid	6 ^c	Minor	0.780	0.608
	TM	7.5 ^c	Minor	0.789	0.623
External Rotation	I-tm	24 ^c	Primary	0.929	0.863
	Posterior Deltoid	5 ^c	Minor	0.895	0.800

^aVolume weighted moment arms (Brown et al., 2007)

^bKuechle et al., 1997

^cKuechle et al., 2000

Table 3**Muscle Volume and Distribution.**

	Volumes (cm ³)		Distribution	
	Mean	SD	Mean	SD
Total Deltoid	185.4	73.3	30.4%	1.2%
Anterior Deltoid	81.8	36.7	43.4% *	3.9% *
Posterior Deltoid	103.6	37.3	56.6% *	3.9% *
PM	143.5	63.8	23.1%	2.2%
TM	79.4	30.8	13.1%	1.2%
Subscapularis	92.7	36.0	15.4%	1.4%
I-tm	79.4	28.3	13.2%	1.1%
Supraspinatus	28.6	10.2	4.8%	0.5%

* The distribution of the anterior and posterior deltoid is relative to the entire deltoid volume. The distribution for all other muscles is relative to the summed volumes of the deltoid, PM, TM, subscapularis, I-tm, and supraspinatus.

Abbreviations: SD= standard deviation (Note, once accepted an appendix with the individual subject data will be provided).