SCAPULOTHORACIC AND GLENOHUMERAL CONTRIBUTIONS TO HUMEROTHORACIC KINEMATICS IN SINGLE VERSUS DOUBLE TENDON TRANSFERS IN BRACHIAL PLEXUS BIRTH INJURY PATIENTS

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

A brachial plexus birth injury (BPBI) occurs in one to four of every 1000 live births, with about a third experiencing long term sequelae[1,2]. Typically, patients with residual C5-6 injuries develop several skeletal and functional deficits such as a decreased range of motion, specifically in external rotation and abduction[3–8]. To improve shoulder function, physicians utilize several procedures including a combination of joint reductions and latissimus dorsi and/or teres major tendon transfers[1,3,17–19,9–16]. The decision to transfer one versus two tendons is at the surgeon's discretion, but recently the surgical decision-making has come under scrutiny. Double tendon transfers have demonstrated greater improvement on external rotation Mallet scores, but single tendon transfers are about 50% less likely to lose midline[20]. Both procedures were shown to have equivalent improvement on Mallet abduction scores[20].

There are limitations with the Mallet classification. Specifically, the classification uses an ordinal scale that assesses HT motion and allows for high variability in patient motion within each grade. Consequently, the Mallet classification lacks precision and cannot differentiate GH and scapulothoracic (ST) contribution to HT motion. This study utilized motion capture to analyze the precise ST and GH contributions to joint function in single and double tendon transfer patients. Children with persistent C5-C6 BPBI's at the time of surgery were recruited at least six months after surgery, allowing for the intended surgical outcomes to take effect. Patients were asked to hold their arm still at several positions including at rest, maximum external rotation, maximum internal rotation, and maximum abduction.

All patients exhibited externally rotated humeral orientations at the GH joint. However, both single and double tendon transfers demonstrated very little GH joint motion from neutral in any position. Instead, tendon transfers appear to re-tension the GH joint into external rotation, but not enough to overcome the ST joint and externally rotate the humerus relative to the patient’s trunk. Our results are contrary to the current literature in several aspects. First, single tendon transfers displayed greater external rotation in all positions compared to double tendon transfers. Second, the double tendon transfer group was able to abduct their arm significantly more than the single tendon transfer group.

Though these results are surprising, they may not be driven by the effect that single or double tendon transfers have on the GH joint. Instead, the results could be impacted by the variation in surgical technique that exists amongst all patients in this study regardless of tendon transfer procedure. All patients’ arms are placed into 90˚ of abduction and externally rotated when the teres major and/or latissimus dorsi tendons are sutured to the humeral head[21]. However, the exact degree of external rotation is variable from patient to patient and can be affected by the surgical methods of joint reduction during surgery. The results indicate that the inclusion of the teres major locks the GH joint into an externally rotated orientation limiting active rotation. It is unclear if the lack of motion postoperatively is driven by the joint reduction, if the tendon transfer exacerbates the reduced motion, or if there is any active GH joint motion preoperatively at all.

Our conclusion calls into question the recommendation of single tendon transfers when patients demonstrate weak internal rotation. The benefit of separating the latissimus dorsi from the teres major does not appear to produce additional benefit as originally believed. In fact, our findings showed the single tendon transfer externally rotated their arm more than double tendon transfers. Unfortunately, this study was limited to isolated teres major and conjoined latissimus dorsi and teres major tendon transfers. Further research on the differing combinations of joint reductions and tendon transfers would better elucidate the roles both tendons play in augmenting GH and ST joint kinematics.

CHAPTER 1

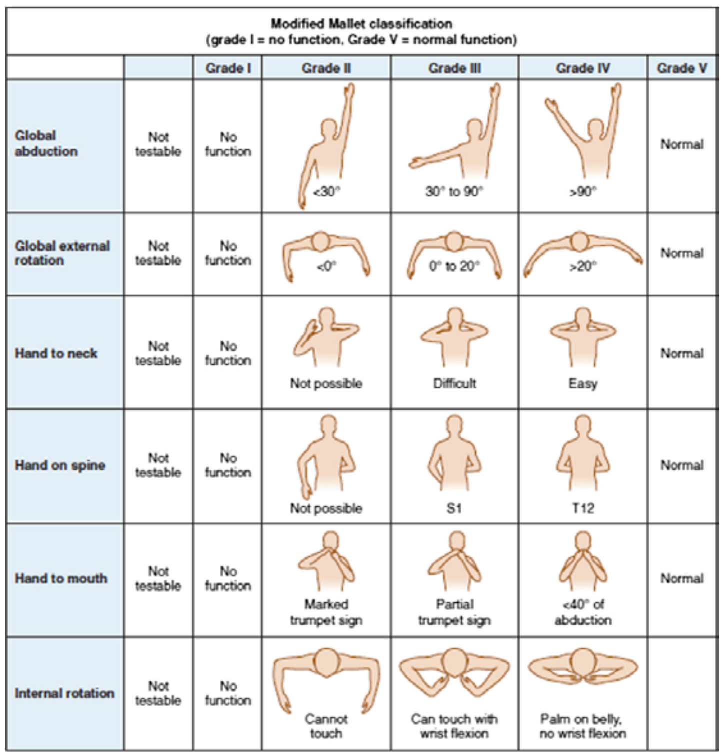
INTRODUCTION

Brachial plexus birth injuries (BPBI) are injuries to the nerve roots of the brachial plexus that typically occur during delivery[1,2]. As a result of the injury, there is persistent weakness about the shoulder especially in external rotation and abduction[19,22–25]. In conjunction, muscle growth of the internal rotators is impeded, leading to internal rotation contractures[26–28]. Internal rotation contractures are more prominent in C5-6 injuries than in C5-7 or global injuries[1,2,22,29,30]. The resultant internal rotation contractures are associated with deformity of the GH fossa, deformity of the humeral head, and posterior subluxation of the humeral head[1,3–5,8,23,31–33]. Deformity and subluxation of the GH joint are related to a loss of shoulder motion, especially in external rotation[6,8,14,18]. Early intervention in the face of progressing GH dysplasia has become a priority in most practices caring for BPBI patients with some patients receiving surgical intervention before their first birthday.

Several procedures can improve GH dysplasia and external rotation, but a lack of abduction often requires tendon transfers of the latissimus dorsi and/or teres major. The latissimus dorsi and teres major are muscles that internally rotate the shoulder from the medial and anterior humerus. Utilizing these muscles to facilitate abduction and external rotation requires the muscles to be excised and then sutured to the posterosuperior aspect of the humeral head[21]. Typically, patients who demonstrate less than 130 degrees of abduction and less than 30 degrees of external rotation receive tendon transfers with joint reduction, while patients who have 30 degrees of external rotation, but less than 135 degrees of abduction receive tendon transfers alone[34]. It is at the discretion of the surgeon to transfer either one (teres major only) or two tendons (both teres major and latissimus dorsi) whenever a tendon transfer procedure is indicated.

There is an abundance of literature confirming the improvement of motion following tendon transfer surgery[13–15,17,18,35]. Many studies assess improvement in functional motion with the modified Mallet classification (Figure 1). The modified Mallet classification is a six-position functional assessment tool designed to assess the level of shoulder function. Waters et al (2008) showed tendon transfers with open joint reduction improved mean aggregate Mallet scores from 10 points preoperative to 18 points postoperative[13]. Waters et al. (2008) also demonstrated that the Mallet score for external rotation improved from two to four, while the internal rotation score (hand-to-spine) improved from one to two. Kozin et al (2006) also showed abduction and external rotation significantly improved by 0.6 and 0.7 respectively[14]. However, Kozin et al. (2006) also saw a significant drop (2.82 ± 0.88 to 2.18 ± 0.53) in Mallet score for the hand-to-spine motion. These results agree that tendon transfers improve external rotation but provide conflicting findings regarding internal rotation.

Several limitations exist with the Mallet classification. Primarily, each grade on the classification contains a wide range of motion (up to 60 degrees) and until recently there was no true measure of internal rotation. Three studies have since expressed concern that the hand-to-spine position does not accurately represent midline function anterior to the body[5,36,37]. Therefore, there has been a gap in knowledge in whether the gain of external rotation and abduction after tendon transfer surgery relates to deficits in internal rotation.



Modified Mallet classification
(grade I = no function, Grade V = normal function)

		Grade I	Grade II	Grade III	Grade IV	Grade V
Global abduction	Not testable	No function	<30°	30° to 90°	>90°	Normal
Global external rotation	Not testable	No function	<0°	0° to 20°	>20°	Normal
Hand to neck	Not testable	No function	Not possible	Difficult	Easy	Normal
Hand on spine	Not testable	No function	Not possible	S1	T12	Normal
Hand to mouth	Not testable	No function	Marked trumpet sign	Partial trumpet sign	<40° of abduction	Normal
Internal rotation	Not testable	No function	Cannot touch	Can touch with wrist flexion	Palm on belly, no wrist flexion	

Figure 1 Modified Mallet classification

Further, the purpose of the tendon transfer surgery is to improve GH motion. However, the Mallet classification only examines HT motion. Utilizing a purely HT measure does not account for the scapula's ability to compensate for the GH joint on the

Mallet scale. Russo et al. (2014) suggested expressing caution when using the Mallet classification to determine shoulder function by showing that ST and GH contributions of varying degrees can obtain the same Mallet score. The study found that GH:ST contribution ratios can range from -0.6:1 to 1.0:1 to achieve the same Mallet score[38]. Russo et al. (2014) also showed that counteractive GH cross-body abduction was masked by increased ST cross-body adduction angles in the hand-to-mouth Mallet position[39]. It is especially pertinent to express caution when assessing shoulder function through Mallet scores postoperatively. This compensatory ability of the scapula in theory could allow for the patient to achieve a greater range of motion, thus creating a perceived functional improvement of the GH joint.

To better describe internal rotation, Abzug et al. (2010) added the hand-to-belly position to the Mallet classification when describing humeral osteotomies. The authors found that while the hand-to-spine position did not significantly change (2.8 to 2.4), there was a significant decrease in hand-to-belly scores (3.7 to 2.9) representing a loss of anterior midline function[40]. A recent study performed the same analysis on tendon transfers to determine the loss of midline (LoM) post-surgery[34]. It was revealed that approximately 20% of children with BPBI will suffer from LoM following tendon transfer surgery with the most affected group being the C5-7 and global injury subgroups[34]. However, there was still an 11% chance of losing midline in the C5-C6 group[34]. Greater frequency of internal rotation contractures in C5-C6 injuries may be responsible for retaining midline function following surgery more often than in patients with lower level injuries. In theory, greater involvement of the nerves that innervate the internal rotators in lower level injuries leads to less severe internal rotation contractures (i.e. worse midline function preoperatively).

Greenhill et al. (2017) compared the LoM of single versus double tendon transfers in residual C5-C6 injuries. His group found that while double tendon transfers had greater improvement in external rotation scores (+2.1) than single tendon transfers (+1.5), the double tendon transfer group had a greater LoM percentage than the single tendon group (35.7% and 14.3% respectively). This finding was noteworthy as it illustrated that both the level of injury and the number of tendons transferred impacted loss of midline function. While Greenhill et al. (2017 & 2018) increased the understanding of tendon transfer surgery on HT motion, there remains a need for deeper understanding of the mechanisms driving motion[20]. Specifically, it is not clear whether the tendon transfers are impacting HT motion by acting primarily on the GH joint, the ST joint, or a combination of both.

In recent years motion capture has been utilized to better understand the GH and ST contributions to overall HT motion[37,38,41,42]. Previous work has shown the ST joint can compensate for lacking or counteractive GH motion to achieve the same arm positions[38,39]. Russo et al. (2014) showed that the affected-arm ST joint displacements in the BPBI population have the potential to be significantly greater than unaffected arms in the external rotation and hand-to-mouth positions[38]. Further, this study also highlighted that patients with C5-6 injuries had less than 20 degrees of GH motion in abduction. This finding suggests that improvements in abduction following tendon transfer might be attributed to other mechanisms, e.g. the scapula[38].

While these findings are substantial, there has yet to be detailed assessment of the GH and ST contributions to motion among BPBI patients who have undergone tendon transfers. In addition, the only comparison between single and double tendon transfers utilized the modified Mallet classification as the assessment method of choice[20]. This study found that there was no significant difference in abduction, but the double tendon transfer group had greater external rotation and a higher percentage of patients demonstrating loss of internal rotation. This study aims to enhance the understanding of mechanisms driving the differences in surgical outcomes, specifically as they relate to abduction, external rotation and loss of midline function in BPBI recipients of single and double tendon transfers.

CHAPTER 2

METHODS

Subjects

Twenty-six postsurgical children with C5-6 BPBI's (age 6.0 ± 1.9 years) participated in this study (Table 1). Participants were recruited prospectively in accordance with the institutional review board for Shriners Hospital for Children – Philadelphia or through retrospective waiver of consent. Thirteen patients with single tendon transfers were matched with 13 double tendon transfer patients based on the following criteria: (1) each pairing was within two points on the combined shoulder sub scores of the AMS or modified Mallet classification, (2) each pairing received the same joint reduction procedure during tendon transfer surgery, and (3) patients within each pair were less than 2 years apart in age at the time of motion capture data collection. All patients must have been at least three years old at the time of data collection.

Table 1 Patient Demographics and histories

			Tendon Transfer	
		Total	Single	Double
Age		6.0 ± 1.9	6 ± 1.9	5.9 ± 2.0
Sex		8 M, 18 F	4 M, 9 F	4 M, 9 F
Age at surgery		1.8 ± 1.2	2.0 ± 1.3	1.6 ± 1.1
Affected Arm				
	Right	13	7	6
	Left	13	6	7
Shoulder joint reduction				
	Open	20	10	10
	Closed	6	3	3

Motion Capture

Patients were seated, and retroreflective markers were placed on the sternal notch, T2 spinous process, T8 spinal process, and the medial and lateral epicondyles of the humerus. Markers for the scapula were placed on the acromion process, trigonum spinae, and inferior angle. Patients were asked to hold their arm extended at their side in six positions: a natural resting position, maximum external rotation, maximum internal rotation, abduction, flexion, and elevation. The trigonum spinae marker and inferior angle marker were re-palpated for each position. Marker positions were recorded for one second in each position with a 12-camera motion capture system (Vicon, Oxford, England, UK) collecting at 60Hz.

When the modified Mallet is administered, the patient's arm is rarely restricted to the plane of motion being assessed. Due to this fact, maximum HT elevation trials were determined by the position (abduction, flexion, or elevation) with the greatest HT elevation angle for each patient. All calculated angles from the patient's peak HT elevation trial were then directly compared between each group as if they were performed with equal instruction from the therapist. The positions were then renamed "maximum HT elevation" and used in analyses.

Data Processing

Coordinate systems for the thorax, humerus and scapula were constructed such that the axes aligned with those recommended by the ISB[43]. Custom written software (LabVIEW 2018, National Instruments, Austin, Texas, USA) was utilized to create ST, GH, and HT joint angles for each position. Scapulothoracic joint angles were calculated using helical angles, while the GH and HT joint angles were calculated using the modified globe method[44–47]. A modified globe method was selected over ISB recommended Euler sequences in order to have an order-independent rotation sequence that will produce clinically observable joint angles for all the positions tested as described by Russo et al. (2016).

Glenohumeral and HT angles are described by elevation angle, internal/external rotation, and cross-body adduction. One deviation was made from the globe method as previously described: internal and external rotation measurements for the GH and HT joint were calculated with zero degrees of rotation representing the epicondylar axis of the humerus aligning with the coronal plane of the scapula and trunk respectively. Scapulothoracic cross-body adduction was also calculated as zero when the scapular plane was parallel to the coronal plane of the trunk. The more anterior the scapula or humerus, the more positive the cross-body adduction angle. The GH, ST and HT joint displacements from neutral were also calculated for each position.

Statistical Analysis

The HT, GH, and ST joint displacements from neutral and all positions collected were compared in separate 2-way multivariate analyses of variance (MANOVAs) utilizing SPSS (IBM Corp, Armonk, NY). There was one between-group factor (single or double) and one within-group factor (Joint = ST, GH, HT). The dependent variables for the internal and external rotation position MANOVAs were the internal/external rotation joint displacements from neutral, while the dependent variables for the abduction, flexion, and elevation position MANOVA's consisted of the joint elevation displacements (upward rotation for ST joint and elevation for GH and HT joints) from neutral. Greenhouse-Geisser corrections were applied when sphericity assumptions were violated for within-subjects' analyses. Pending significant between-group interactions, post-hoc discriminant function analyses (DFA) were performed with the dependent variable as surgical group and the three joint displacements as the independent variables. The same approach was used to compare the joint angles for each position.

CHAPTER 3

RESULTS

Joint Displacements

The MANOVA for external rotation displacements during external rotation did not yield significant results ($F_{2,23} = 0.809$, $p = 0.386$) between joints (ST, GH, HT) **or** between groups ($F_{2, 23} = 0.915$, $p = 0.348$). Therefore, no DFA was implemented to find specific group differences. Additionally, the MANOVA for internal rotation yielded significant differences between joints ($F_{2,23} = 0.263$, $p = 0.653$), but failed to find a significant difference between groups ($p = 0.415$). Since differences between joints were not of interest, no post-hoc analysis was performed on these variables. Joint displacement means for internal and external rotation displacements can be found in Table 2.

Table 2 Subject joint displacements from neutral. All values are in degrees.

External Rotation	ST		GH		HT	
Single	0.7	(± 10.6)	2.6	(± 10.2)	9.1	(± 14.3)
Double	3.0	(± 11.1)	6.9	(± 11.7)	15.5	(± 17.9)
Internal Rotation						
Single	0.6	(± 7.7)	10.8	(± 10.6)	11.2	(± 13.7)
Double	2.4	(± 5.5)	15.4	(± 10.6)	16.4	(± 13.3)

Displacements are positive in external rotation for the external rotation position, displacements are positive for internal rotation for the internal rotation position, *Indicates significant differences

The MANOVA for elevation displacements during abduction produced significant results ($F_{2,23} = 812.654$, $p = 0.000$) between joints (ST, GH, HT), but *not* between surgical groups ($F_{2, 23} = 1.018$, $p = 0.323$). Therefore, no DFA was implemented. Additionally, the MANOVA for peak HT elevation also yielded significant results ($F_{1,30} = 1185.755$, $p = 0.000$) between joints, but failed to find a significant results between groups ($p = 0.256$). Since differences between joints were not of interest, no post-hoc analysis was performed on these variables. Joint displacement means for abduction and peak HT elevation can be found in Table 3.

Table 3 Joint elevation displacements from neutral

Abduction	ST		GH		HT	
Single	65.4	(± 11.7)	22.2	(± 17.8)	87.5	(± 17.1)
Double	70.4	(± 15.5)	27.6	(± 12.1)	100.8	(± 12.4)
Peak HT Elevation						
Single	69.8	(± 11.7)	24.4	(± 17.8)	94.3	(± 17.1)
Double	72.5	(± 15.5)	29.8	(± 12.1)	105.7	(±12.4)

Positive displacements indicate ST upward rotation and GH/HT elevation, no significant differences existed

Joint Angles

For the joint angles during external rotation, the MANOVA did not yield significant results between joints ($F_{1,28} = 0.411$, p = 0.558) **or** between groups ($F_{2, 23} = 3.246$, p = 0.084). Therefore, no DFA was implemented to find specific group differences. However, the MANOVA for the joint angles during internal rotation yielded significant results ($F_{2,23} = 318.631$, p = 0.000) between joints **and** between groups ($F_{1, 24} = 8.302$, p = 0.008). Following the MANOVA, a statistical significance ($p > .05$)

stepwise discriminant function analysis was employed to evaluate the relative contribution of the dependent variables. The function was statistically significant (Wilks λ = .735, $\chi 2$ = 7.229, df [1], p = .007) and accounted for 26.5% of the between group variability. An examination of the standardized coefficients also showed that only the HT external rotation angle made a significant, unique contribution to the function. A classification analysis that used a "leave one out" cross validation approach to guard against positively-biased classifications correctly identified 61.5% of all cases using the HT external rotation angle. At the same time, 61.5% of cases were correctly identified for both the single and double tendon transfer groups individually.

A secondary follow-up utilizing univariate ANOVAs was also performed. The dependent variables for each ANOVA consisted of the internal rotation angles for each joint and the independent variable was the tendon transfer type. The univariate results showed single tendon transfers had significantly more external rotation at the GH *and* HT joints ($F_{1,24}$ = 7.924, p = 0.010 and $F_{1,24}$ = 8.644, p = 0.007, respectively). In contrast, the ST external rotation angles were not significantly different between surgical groups (p = 0.195). Internal and external rotation joint angles can be found in Table 4.

Based on the results of the first two positions, the joint range of motion for both positions was essentially identical between groups. However, the joint angles were significantly different for internal rotation but not for external rotation. This created a conflict as the range of motion and joint angles for internal rotation did not mirror each other like the external rotation position. Therefore, univariate ANOVAs were also performed for the neutral position as starting position could account for the aforementioned discrepancy. The dependent variables for each ANOVA consisted of the internal/external joint angles for each joint and the independent variable was tendon transfer type. The univariate results revealed single tendon transfers had significantly more external rotation at the GH and HT joint with their arm at rest ($F_{1,24} = 5.177$, $p = 0.032$ and $F_{1,24} = 4.904$, $p = 0.037$, respectively). Conversely, the ST joint internal/external rotation angles had no significant differences between the surgical groups ($p = 0.119$). Neutral joint angles can be found in Table 4.

Table 4 Subject Joint angles with the arm adducted

Neutral	ST		GH		HT	
Single	48.5	(± 5.3)	-33.1*	(± 22.6)	15.3*	(± 20.7)
Double	44.3	(± 7.8)	-13.1*	(± 22.2)	34.6*	(± 23.6)
External Rotation						
Single	-47.0	(± 12.6)	35.8	(± 25.2)	-6.4	(± 19.6)
Double	-40.2	(± 13.3)	20.1	(± 25.6)	-19.2	(± 30.6)
Internal Rotation						
Single	48.5	(± 9.0)	-22.3*	(± 21.6)	26.6*	(± 19.5)
Double	45.2	(± 7.4)	2.4*	(± 23.1)	51.0*	(± 22.7)

External rotation angles are expressed positively in external rotation, internal rotation angles are expressed positively in internal rotation and neutral, *Indicates significant differences

For the joint angles during abduction, the MANOVA yielded significant results ($F_{2,23} = 1359.236$, p = 0.000) between joints *and* between groups ($F_{2, 23} = 4.379$, p = 0.047). Following the MANOVA, a stepwise discriminant function analysis was employed to evaluate the contribution made by dependent variables in distinguishing between groups. The discriminant function was statistically significant (Wilks $\lambda = .785$, $\chi2 = 5.694$, df [1], $p = .017$) and accounted for 21.5% of the between group variability. An examination of the standardized coefficients also showed that only the HT elevation angle made a significant, unique contribution to the function. The function was evaluated through a classification analysis. The adjusted, “leave one out” classification matrix correctly identified 69.2% of all cases using the HT elevation angle. 69.2% of cases were correctly identified for both single and double tendon transfers.

A secondary follow-up utilizing univariate ANOVAs was also assessed. The dependent variables for each ANOVA consisted of the elevation angles of each joint and the independent variable was tendon transfer type. The univariate results showed double tendon transfers had significantly more GH and HT elevation than the single tendon transfer group ($F_{1,24} = 4.349$, $p = 0.048$ and $F_{1,24} = 6.580$, $p = 0.017$, respectively). ST upward rotation angles were not significantly different between surgical groups ($p = 0.372$). elevation angles for abduction can be found in Table 5.

The MANOVA for the joint angles during peak HT elevation yielded significant results ($F_{2,23} = 1896.592$, $p = 0.000$) between joints, but *not* between groups ($F_{2, 23} = 3.799$, $p = 0.063$). Therefore, no DFA was implemented to find specific group differences. Since HT elevation angles for abduction were able to discriminate between surgical groups, but the MANOVA for peak HT elevation angles was just short of significance, a follow-up analysis was done utilizing univariate ANOVAs for peak HT elevation joint angles. The dependent variables for each ANOVA consisted of the elevation angles for each joint (upward/downward rotation for the ST joint) and the independent variable was the tendon transfer type. The univariate results showed double tendon transfers had significantly more elevation for the HT joint ($F_{1,24} = 5.184$, $p = 0.032$). Although the double tendon transfer group trended toward higher GH elevation angles, the ST and GH elevation angles were not significantly different between surgical groups ($p = 0.639$ and $p = 0.072$, respectively). Peak HT elevation angles can be found in Table 5.

Table 5 Joint elevation angles

Neutral	ST		GH		HT	
Single	-5.9	(± 9.0)	45.5	(± 14.2)	30.1	(± 9.0)
Double	-8.0	(± 8.7)	53.5	(± 17.0)	35.3	(± 9.8)
Abduction						
Single	52.5	(± 12.2)	67.7	(± 15.4)	117.7	(± 20.7)
Double	56.3	(± 9.1)	81.1	(± 17.3)	136.2	(± 15.6)
Peak HT Elevation						
Single	56.8	(± 7.6)	71.2	(± 15.6)	125.2*	(± 18.2)
Double	58.4	(± 9.6)	83.3	(± 17.1)	141.0*	(± 17.3)

Positive numbers indicate ST upward rotation and GH/HT elevation,
*Indicates significant differences

Due to the significant differences found in the external/internal rotation angles in the neutral position, univariate ANOVAs were also performed for the neutral position elevation angles. The dependent variables for each ANOVA consisted of the joint elevation angles (upward/downward rotation for the ST joint) and the independent variable was tendon transfer type. The univariate results revealed no significant differences for the ST, GH, or HT joints ($p = 0.55$, $p = 0.20$, $p = 0.17$, respectively) and both groups started in essentially the same degree of elevation.

CHAPTER 4

DISCUSSION

Scapulothoracic and GH joint kinematics for positions with the arm adducted

The results of this study indicate that single tendon transfers are more externally rotated than double tendon transfers throughout the entire arc of axial rotation. Yet, both tendon transfer groups are almost identical in achievable range of motion from neutral, regardless of the direction of rotation. In fact, both groups have very little capacity to rotate their humerus at the GH joint (Table 2). The greatest amount of rotation was achieved by the double tendon transfer group during internal rotation, and this consisted of 16˚ of GH rotation. In theory, the tendon transfer procedure is designed to increase active external rotation and abduction at the GH joint, creating better scores on functional measurements. These results should be interpreted with caution as they have several clinically meaningful indications.

The tendon transfer procedure appears to improve functional measurement scores by essentially "locking" the GH joint in external rotation at the posterior rotator cuff creating a scapulohumeral unit (SHU). This unit can allow for more free movement of the scapula and take advantage of measures like the Mallet classification that favors movements requiring GH and HT external rotation. A lack of presurgical 3D coordinate data is typical in this population but undermines our ability to determine if the GH joint has lost its presurgical range of motion, or if the 10-15˚ of displacement is possible *because* of the procedure. However, one patient did have preoperative motion capture data and can provide some insight. Subject 2 (single tendon transfer, surgical reduction) was in 14˚ of GH internal rotation in neutral preoperatively (Table 6) compared to 27˚ of external rotation postoperatively. Not only is this change approximately 40˚, but the GH joint’s orientation has crossed neutral (Figure 2). Contrary to the GH joint, the ST joint has essentially zero change in internal rotation from surgery (46˚ to 48˚). This would mean the joint reduction in conjunction with tendon transfer does not affect the ST joints axial rotation, but externally rotates the GH joint, improving the resting position of the humerus. The HT joint remains internally rotated, but the amount of rotation decreased from 62˚ to 23˚ or approximately 40˚. Similar to the current postoperative cohort, Subject 2 also had very little active GH motion preoperatively as the joint displacement was 10˚ in external rotation (compared to 2.6˚ for single and 6.9˚ for double tendon transfers) and essentially 0 in internal rotation (10.8˚ for single and 15.4˚ double tendon transfers).

Table 6 Subject 2 preoperative joint angles and displacements

	Joint angles			Joint displacements		
Position	ST	GH	HT	ST	GH	HT
Neutral	46.0	14.0	62.0			
External Rotation	-50.0	-4.0	-50.0	-2.0	10.0	12.0
Internal Rotation	49.0	13.0	62.0	3.0	1.0	0.0

All positions are represented in degrees of internal rotation

Based on this patient’s data, it would appear that in addition to reorienting the GH joint, patients may see a mild increase in active internal rotation after surgical joint reduction and tendon transfers. However, it must be emphasized that BPBI patient’s upper extremity is severely internally rotated due to internal rotation contractures, as shown by Subject 2’s 62˚ of HT internal rotation at rest. It is likely that this patient’s trunk is impeding further active internal rotation on the Mallet test. Moreover, if this patient could achieve greater active internal rotation, it would likely not be evident because their posture allows them to touch their abdomen. This institution uses the hand-to-belly position to represent internal rotation and approximately 60% of BPBI patients can achieve this. It must also be emphasized that this patient received a surgical joint reduction which could be the sole driver of the increased external rotation.

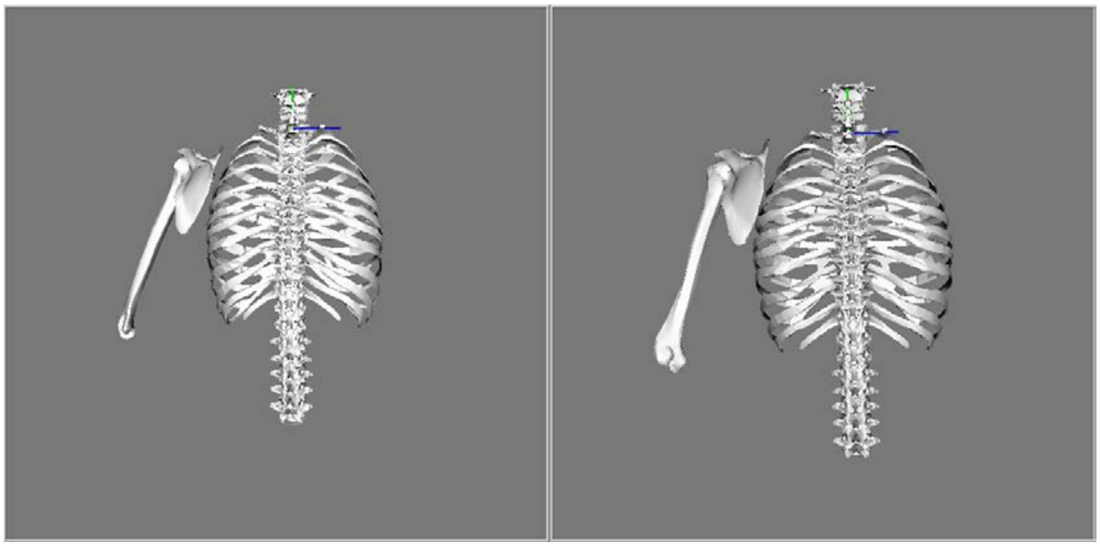


Figure 2 Subject 2 neutral resting position preop (left) and postop (right)

The effect of “locking” the GH joint is apparent when looking at the joint angles for all three positions together. In neutral, both groups begin internally rotated from the orientation of the ST joint, a common visible trait seen as scapular winging in most BPBI patients[29,39]. Consequently, both groups hold their upper extremity in internal rotation when assuming a neutral posture. However, the GH joint is more externally rotated by 20˚ in the single tendon transfer group compared to the double tendon transfer group (Table 3). Approximately 20˚ of greater GH and HT external rotation can be seen throughout all three positions. In the external rotation position, there is essentially no change in the joint angles from neutral and continued internal rotation posturing. Subject 16 had the greatest external rotation angle and is shown in Figure 3 to demonstrate the lack of rotation. While in internal rotation, the double tendon transfer group achieves a small amount of GH internal rotation and the single tendon transfer group remains externally rotated at the GH joint. These findings are significant and are reflected clinically by single tendon transfers slightly lower internal rotation Mallet scores (single = 2.8, double = 3.1). However, even though there was approximately a 15˚ difference, the GH and HT external rotation joint angles did not reach significance, which is also reflected clinically on Mallet external rotation scores (single = 3.5, double = 3.5).

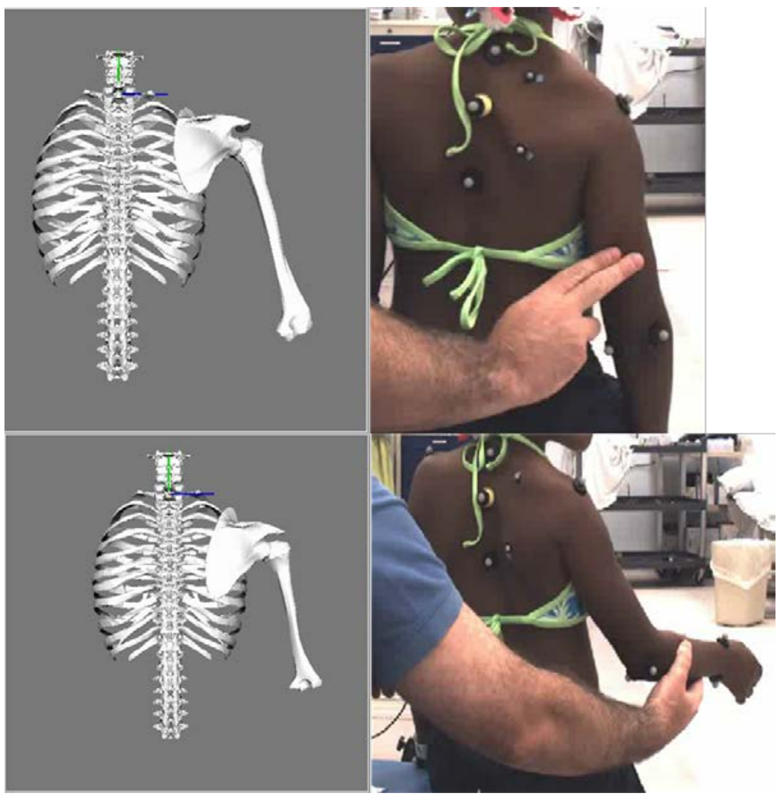


Figure 3 Change in humeral positioning in neutral and external rotation Subject 16 (greatest amount of external rotation displacement from neutral)

These results are in contrast to the recommendations provided by both Greenhill (2017) and Abzug (2018). While both studies recommend a single teres major tendon transfer when internal rotation is weak, our results indicate the recommendation may be ill advised. The current cohort's single tendon transfer group is more externally rotated, but functional outcomes may be driven more by perioperative factors than tendon transfer type. During surgery, the anteroinferior portion of the GH joint capsule is released. Then, if adequate external rotation is not achieved, the subscapularis and/or pectoralis major may be further released or elevated at its insertion. Finally, the patient's arm is placed into 90˚ of abduction and the humerus is externally rotated as the sutures are tightened to the humeral head[21]. Therefore, the degree of passive external rotation may be a significant factor impacting the results. Several factors can contribute to passive external rotation including type of joint release, subscapularis release, prior Botox injections, Waters classification, or glenoid deformity type.

When subjects were stratified on joint reduction type and not tendon transfer, the patients with surgical joint reductions (arthroscopic or open) saw a significant increase in GH and HT external rotation orientations compared to the closed joint reduction group (Table 7). In fact, the surgical joint reduction group (n = 20) was more externally rotated in every position compared to the closed reduction group (n = 6). Conversely, there was no significant difference in joint displacements based on joint reduction. The results are analogous to the results stratified on tendon transfer type indicating the single tendon transfer patients may have more adequate joint releases. Two subjects with single tendon transfers required additional release of the subscapularis and/or pectoralis compared to none of the double tendon transfers (Table 1). As mentioned before, Abzug et al. (2018) suggests additional release or elevation of the subscapularis tendon may be needed for additional external rotation[21]. The impact of this additional release is evident in Subject 11's kinematics as they had the most external rotation at the GH joint of any subject in either group. This subject was the only patient to have a release of the subscapularis and pectoralis major. Removing the subjects with subscapularis releases and their matches from statistical analysis affected significance on several positions, but the single tendon transfer group still trended towards 15 or 20˚ of greater external rotation angles in all positions.

Table 7 Joint rotation angles based on joint reduction type

Neutral	ST		GH		HT	
Closed	47.7	(± 7.0)	-8.7	(± 28.4)	41.8*	(± 29.1)
Surgical	46.1	(± 7.0)	-27.0	(± 21.8)	19.9*	(± 20.3)
External Rotation						
Closed	-48.5	(± 10.1)	12.3	(± 30.5)	-33.0*	(± 27.8)
Surgical	-42.0	(± 13.8)	32.6	(± 23.6)	-6.7*	(± 22.8)
Internal Rotation						
Closed	45.7	(± 5.9)	3.7*	(± 26.4)	53.5*	(± 24.9)
Surgical	47.2	(± 8.9)	-14.1*	(± 24.1)	34.4*	(± 22.7)

Neutral and internal rotation are represented in degrees of internal rotation, external rotation is represented in degrees of external rotation, * indicates significance

The results of this study call into question the need for transferring the latissimus dorsi with the teres major, *period*. Pearl et al. (2006) showed isolated latissimus dorsi transfers in combination with arthroscopic anterior release can improve external rotation and GH joint remodeling, but the improved external rotation came with varied loss of internal rotation in all patients[36]. However, this cohort also included release of the subscapularis in conjunction with anterior capsular release. All patients tested with only anterior capsule and subscapularis releases were unable to press their hand to their abdomen, and patients with both release and isolated latissimus dorsi transfers also reported decreased internal rotation. Additionally, this cohort exhibited no substantial increase in humeral elevation following pure release *or* release and isolated latissimus dorsi transfer. Several other studies have suggested isolated latissimus dorsi transfer can improve abduction and external rotation[48–50], but these studies neglected to exclude patients with concomitant teres major transfers, teres major tenotomies, lower trunk injuries, subscapularis releases, and pectoralis lengthening's from their results, making the claim untenable. One group also had larger differences in group size and measured both external rotation and abduction simultaneously[49].

Ruyer et al. (2018) found that arthroscopic anterior release without tendon transfers and subscapularis sparing increased external rotation both passively and on Mallet[10]. However, active elevation was not substantially improved with an average increase of 0.3 on Mallet abduction scores. The authors concluded that the procedure increased external rotation while also retaining internal rotation up to two years post-surgery. Unfortunately, the authors measured internal rotation using the hand to spine position, which has been shown to be a poor measure of internal rotation[37,40]. Conversely, Kozin et al. (2010) found that the inclusion of subscapularis release in conjunction with an anterior capsular release did increase abduction on Mallet, but the authors suggested the different outcome could be due to surgical technique, immobilization, and rehabilitation differences[51].

There is scant literature on the effects of closed reduction in conjunction with tendon transfers and the findings of other previous studies involving joint releases are hard to clarify in the context of this study considering the mixture of surgical procedures and levels of injury throughout. Two studies performed closed reduction and tendon transfers, but also included a “Z-plasty” or release of the pectoralis major[17,52]. The patients in both cohorts showed improved abduction and external rotation postoperatively, but the additional involvement of the pectoralis major adversely impacted the results. Additionally, patients’ motion was assessed utilizing a scale where the arm is abducted and externally rotated simultaneously[52]. Similarly, there is scarce literature on the effects of closed reduction alone. Greenhill et al. (2018) followed 49 patients who underwent closed reduction and concomitant botulinum toxin type A injections and found 84% would eventually go on to have additional procedures to improve external rotation[53].

Based on the literature detailed here and the current findings, few conclusions can be drawn. It is apparent from the current cohort that active GH joint motion is not clinically noticeable after tendon transfer surgery. The joint becomes immobile and most active motion comes from the scapula, which could influence the improvement of functional assessments. Further, the improvement on the modified Mallet classification for external rotation is most likely due to joint releases. The patients receiving joint releases were significantly more externally rotated than those that did not receive a surgical release. The benefit of single tendon transfers could potentially be seen in the adduction angles during external rotation. In theory, leaving the latissimus dorsi intact in the single tendon transfer group would retain shoulder adduction potentially lost when the muscle is transferred to the posterior cuff. While significance was not found, the single tendon transfers trend toward higher GH and HT adduction angles than the double tendon transfer group (Appendix C).

It should be noted that both tendon transfer groups have three patients who are unable to reach midline via Mallet at the time of data collection. Five of six having surgical joint reductions and three eventually receiving de-rotational humeral osteotomies. Recommending single teres major transfers for BPBI patients requiring increased abduction and external rotation cannot be done without further examination of the subject's abduction scores.

The relationship of joint kinematics during elevation with positions of adduction

The results of the abduction and peak HT elevation positions in this study indicate that double tendon transfer patients can elevate their humerus more than single tendon transfer patients irrespective of plane of elevation. Although the MANOVA for peak HT elevation angles only approached significance on the between group factor, the univariate ANOVAs found a significant difference between groups for HT elevation angles during peak HT elevation. A DFA following the significant MANOVA for abduction was able to discriminate group membership for approximately $3/4^{th}$'s of the patients in the study. Similar to findings for external rotation, both tendon transfer groups were almost identical in achievable range of motion from neutral (Table 5). Additionally, although these results showed a larger range of motion, there were consistencies with the findings for changes in external rotation that demonstrated minimal GH motion from neutral.

The abduction and peak HT elevation positions were almost identical within each group but, the greatest amount of active GH elevation was observed in the double tendon transfer group during peak HT elevation, which amounted to 29˚ of elevation from neutral. While 30˚ may be clinically noticeable for external rotation, each modified Mallet score for abduction encompasses a 60˚ range, most likely making increases solely at the GH joint indistinguishable on clinical exam. However, Subject 2 can provide similar insight for peak HT elevation as for the internal/external rotation positions.

Subject 2 (single tendon transfer) was able to reach 50˚ of GH elevation preoperatively (Table 8) compared to 63˚ postoperatively. Only about a 10˚ change. Similarly, the ST joint's change in upward rotation from surgery was 52˚ to 63˚ and the HT joint increased from 107˚ to 121˚, or about 10˚. This appears as though the tendon transfer increased GH joint motion by a small degree, but the real changes lie in the resting position and joint displacements. The resting position for Subject 2 was in 17˚ of upward rotation at the ST joint, 11˚ of elevation for the GH joint, and 21˚ of elevation at the HT joint compared to the postoperative positioning of 7˚, 17˚, and 19˚ (ST, GH, HT joints respectively) of elevation for the postoperative resting position. Indicating the resting position has not changed. However, the joint displacements have changed from ST upward rotation of 45˚ to 64˚, GH elevation of 40˚ to 46˚, and HT elevation from 86˚ to 103˚. Based on the subject's kinematics, it appears tendon transfers do not increase active GH elevation as intended, but instead enable the scapula to rotate further upward, allowing for a higher peak HT elevation. This is further realized in the full cohort of subjects.

Table 8 Subject 2 joint elevation angles and displacements

	Joint angles			Joint displacements		
Position	ST	GH	HT	ST	GH	HT
Neutral	17.0	11.0	21.0			
Abduction	52.0	50.0	107.0	45.0	40.0	86.0

ST joint is represented by upward rotation, GH and HT joints are represented by elevation

Approximately 70% of all active HT elevation appears to come from the ST joint in both groups. Previous studies have shown that arthroscopic anterior releases with or without latissimus dorsi tendon transfers increase “active” external rotation but have no substantial impact on active elevation[10,12,54]. While one study did find that anterior capsular and subscapularis release significantly increased active abduction[51], the increase was only approximately 15˚. Although isolated latissimus dorsi transfers and anterior releases limited internal rotation, it appears the primary source of limitation was the subscapularis release. We concluded based on our findings of external and internal rotation joint displacements that the teres major must help “lock” the GH joint in external rotation as well. The findings in this chapter further support the theory that the teres major is “locking up” the GH joint, but while the joint is locked in external rotation, this also allows for the scapula and humerus to elevate as a unit. This is further evident from the external rotation angle during peak HT elevation.

To test the scapulohumeral unit theory, univariate ANOVAs were run with the three joints internal/external rotations angles during peak HT elevation as dependent variables and tendon transfer type as independent variables. The univariate results showed single tendon transfers had significantly more external rotation at the GH joint ($F_{1,24} = 5.068$, $p = 0.034$) than double tendon transfers. In contrast, the ST and HT external rotation angles were not significantly different between surgical groups ($p = 0.230$ and $p = 0.458$, respectively). Internal and external rotation joint angles during peak HT elevation can be found in Table 9. These results indicate that the humerus is “locked” to the scapula in external rotation allowing for the humerus to elevate *with* the scapula as a unit. However, while more externally rotated, the single tendon transfer group loses some external rotation compared to the double tendon transfer group.

Table 9 Internal and external rotation angles during peak HT elevation

	ST		GH		HT	
Single	43.1	(± 8.1)	-41.2*	(± 21.2)	20.8	(± 22.4)
Double	39.0	(± 8.8)	-21.7*	(± 23.0)	27.5	(± 22.8)

Joint angles are represented in internal rotation, * indicates significant differences

The change in orientation can be also seen again in Subject 2's pre-to-postoperative data. Subject 2 saw no change in ST external rotation during abduction (-50˚ for both data collections) but demonstrated a 20˚ increase in GH external rotation from pre to post-operative data collections (13˚ and 34˚ respectively). Surprisingly, the HT joint saw essentially no change (-26˚ to -28˚) in external rotation despite the large difference in the GH joint (Table 10). The abduction position for Subject 2 was the peak HT elevation angles used both pre and post-operatively. Although not a uniform position, we believe more emphasis should be placed on the peak HT elevation joint angles than abduction joint angles. Scores for abduction are prone to errors based on examiner instruction. On Mallet, there is no restriction of the upper extremity to move in the plane of abduction allowing for multiplanar motion. Kinematically, pure abduction may be missed due inconsistent or poor examiner instruction on the plane of elevation. However, comparing multiple positions regardless of plane allows for direct comparison of maximum HT elevation regardless of examiner instruction.

Table 10 Subject 2 preoperative external rotation angles during abduction

	ST	GH	HT
PreOp	-50.0	13.0	-26.0
PostOp	-50.0	34.0	-28.0

All angles are represented in external rotation

Utilizing this position, it is apparent both tendon transfer procedures are experiencing similar impacts on motion, but the double tendon transfer is increasing humeral elevation significantly more than the single tendon transfers. As Pearl et al. (2006) found, the latissimus dorsi in conjunction with anterior releases did not significantly increase humeral elevation, but they did report an increase of approximately 10˚. Considering these results, it appears the latissimus may actually play a supportive role in elevating the humerus. However, this conclusion is purely speculative. It is unknown if the increased external rotation of the humerus during HT elevation limited the single tendon transfer group from fully elevating their HT joint, or if the latissimus dorsi helped increase HT elevation by 10 or so degrees. The latissimus dorsi may also play preventative role in the single tendon transfer group.

In theory, the single tendon transfer groups could potentially be restricted by the latissimus dorsi when the tension on the muscle maximizes at a certain elevation. Previous studies have shown that injuries to the brachial plexus nerve roots impede muscle growth and could be the primary factor in internal rotation contractures[26–28]. Although the extent of injury to the C6 nerve in each patient is unknown, the nerve root partially innervates the latissimus dorsi and could impede growth. Limiting the growth of the latissimus dorsi could then create a resistant force on the GH joint as the arm is raised to increasing degrees of elevation. This effect would not be experienced in the double tendon transfer group due to the relocation of the latissimus dorsi closer to the GH joint than its original insertion.

While the results of the joint elevation angles support the GH joint "locking" theory by the teres major, the significant differences between tendon transfer groups for HT elevation angles during peak HT elevation presents a conflict with the results for external/internal rotation positions. The results from all positions support joint reduction and tendon transfer procedures lock the GH joint into an external rotation orientation and allow for the scapula to move more freely. The internal and external rotation positions support eliminating the latissimus dorsi from the procedure, while the peak HT elevation position needs further investigation to determine its role. The results may further be muddied by the surgical joint releases. To investigate the effects of joint release on HT elevation a MANOVA was utilized with joint elevation angles as the dependent variables and joint reduction type as the independent variables. Although significance was not found ($p = 0.092$), Table 11 shows the closed tendon transfer procedures demonstrate a greater humeral elevation compared to the surgical joint reduction group. Therefore, it is unclear whether the latissimus would impact HT elevation in the single tendon transfers at all or if the singles received greater joint release during surgery.

Table 11 Closed versus surgical joint reduction peak HT elevation angles

Neutral	ST		GH		HT	
Closed	-10.0	(± 10.9)	60.2	(± 14.5)	38.5	(± 7.8)
Surgical	-6.1	(± 8.0)	46.3	(± 15.2)	31.0	(± 9.5)
Abduction						
Closed	52.2	(± 4.6)	82.8	(± 20.8)	134.3	(± 27.1)
Surgical	55.1	(± 12.0)	72.0	(± 16.0)	124.7	(± 18.1)
HT elevation						
Closed	57.0	(± 5.9)	88.8	(± 19.5)	145.8	(± 25.3)
Surgical	57.8	(± 9.3)	73.8	(± 15.3)	129.3	(± 15.7)

Joint elevation is represented as upward rotation for the ST joint and elevation for the GH and HT joints, no significant differences were found

The conclusions of this study are limited by the inclusion of only isolated teres major and conjoined latissimus dorsi and teres major tendon transfers. Including isolated teres major transfers with latissimus dorsi tenotomy to this cohort would improve understanding of the role each tendon plays in augmenting shoulder kinematics. Further research in joint kinematics on the different combination of joint releases and tendon transfers is needed to parse the contributions of each technique to shoulder function. Based on our findings, we believe single isolated teres major transfers for patients with weak internal rotation may be ill advised without further examination.

CONCLUSION

Brachial plexus birth injuries occur in approximately one out of every 1000 live births and can lead to lifelong paralysis of upper extremity functions. While several surgeries are implanted to improve shoulder function there remains unanswered questions on the specific impact's surgery has on patients. Scapulothoracic and GH contributions to shoulder function have been historically difficult to assess in the clinic, but the recent application of motion capture technology has greatly increased the understanding of the kinematics that drive shoulder function in the BPBI population[37–39,41,44,45].

This study utilized motion capture technology to investigate a current issue in the surgical algorithm for implanting tendon transfer surgery. We established a stronger understanding of how tendon transfers impact the shoulder complex and whether single or double tendon transfers are equivalent procedures. We found that each surgery had its intended effect of externally rotating the humerus at the GH joint, but with unexpected traits. Our results show the GH joint is re-tensioned or locked from surgery into a more externally rotated orientation. However, our results did not exactly align with the current literatures belief tendon transfers increase active external rotation. We found that the double tendon transfer did not create increased external rotation *or* prevent internal rotation any more than single tendon transfers. In fact, our findings indicate the current recommendation to transfer a single tendon to retain internal rotation post-surgery may be ill-advised.

The study also investigated the role each surgery had on elevation. The current belief that both procedures are equivalent at increasing humeral elevation was not observed. We were able to accurately determine which surgery was performed approximately 75% of the time based solely on the level of HT elevation. However, we believe that these results could be affected by perioperative factors including greater joint release in the single tendon transfer patients. The intact latissimus dorsi my also contribute to limiting elevation if there is substantial denervation. Based on the findings in this study and the available literature, it appears the improvements seen in patient shoulder function come from the type of joint reduction and the teres major transfer. While the latissimus dorsi may provide tension like elements, we believe the latissimus dorsi tendon has a small, possibly insignificant, impact on shoulder function whether positive or negative.

The findings of this study addressed several questions designed to improve our understanding of the impact single versus double tendon transfers have on ST and GH joint function. Based on our results, we believe the recommendation of isolated teres major transfer for patients with weak internal rotation may be ill advised. Additional conclusions cannot be made without further investigation.

REFERENCES

1. Buterbaugh KL, Shah AS. The natural history and management of brachial plexus birth palsy. *Curr Rev Musculoskelet Med*. 2016;9(4):418-426. doi:10.1007/s12178-016-9374-3.

2. Hoeksma AF, Wolf H, Oei SL. Obstetrical brachial plexus injuries: Incidence, natural course and shoulder contracture. *Clin Rehabil*. 2000;14(5):523-526. doi:10.1191/0269215500cr341oa.

3. Bae DS, Waters PM. Brachial Plexus Birth Palsy: The Boston Children's Hospital Experience. *Semin Plast Surg*. 2004;18(4):275-283. doi:10.1055/s-2004-837254.

4. Kozin SH. Correlation between external rotation of the glenohumeral joint and deformity after brachial plexus birth palsy. *J Pediatr Orthop*. 2004;24(2):189-193. doi:10.1097/01241398-200403000-00011.

5. Kozin SH. The evaluation and treatment of children with brachial plexus birth palsy. *J Hand Surg Am*. 2011;36(8):1360-1369. doi:10.1016/j.jhsa.2011.05.018.

6. Pearl ML, Edgerton BW. Glenoid deformity secondary to brachial plexus birth palsy. *J Bone Joint Surg Am*. 1998;80(5):659-667. http://www.ncbi.nlm.nih.gov/pubmed/9611026.

7. Bhardwaj P, Burgess T, Sabapathy SR, Venkataramani H, Ilayaraja V. Correlation Between Clinical Findings and CT Scan Parameters for Shoulder Deformities in Birth Brachial Plexus Palsy. *J Hand Surg Am*. 2013;38(8):1557-1566. doi:10.1016/j.jhsa.2013.04.025.

8. Waters PM, Jaramillo D. Glenoid deformity secondary to brachial plexus birth palsy. *J Bone Joint Surg Am*. 1998;80(5):659-667. http://www.ncbi.nlm.nih.gov/pubmed/9611026.

9. Elzohairy MM, Salama AM. Evaluation of functional outcomes and preliminary results in a case series of 15 children treated with arthroscopic release for internal rotation contracture of the shoulder joint after Erb's palsy. *J Child Orthop*. 2016;10(6):665-672. doi:10.1007/s11832-016-0773-1.

10. Ruyer J, Grosclaude S, Lacroix P, et al. Arthroscopic isolated capsular release for shoulder contracture after brachial plexus birth palsy : clinical outcomes in a prospective cohort of 28 children with 2 years ' follow-up. *J Shoulder Elb Surg*. 2018. doi:10.1016/j.jse.2018.01.022.

11. Pedowitz DI, Gibson B, Williams GR, Kozin SH. Arthroscopic treatment of

posterior glenohumeral joint subluxation resulting from brachial plexus birth palsy. *J Shoulder Elb Surg*. 2007;16(1):6-13. doi:10.1016/j.jse.2006.04.008.

12. Pearl ML. Arthroscopic release of shoulder contracture secondary to birth palsy: An early report on findings and surgical technique. *Arthrosc - J Arthrosc Relat Surg*. 2003;19(6):577-582. doi:10.1016/S0749-8063(03)00390-6.

13. Waters PM, Bae DS. The Early Effects of Tendon Transfers and Open Capsulorrhaphy on Glenohumeral Deformity in Brachial Plexus Birth Palsy. *J Bone Jt Surg*. 2008;90(10):2171-2179. doi:10.2106/JBJS.G.01517.

14. Kozin SH, Chafetz RS, Barus D, Filipone L. Magnetic resonance imaging and clinical findings before and after tendon transfers about the shoulder in children with residual brachial plexus birth palsy. *J Shoulder Elb Surg*. 2006;15(5):554-561. doi:10.1016/j.jse.2005.11.004.

15. Kozin SH, Chafetz RS, Shaffer A, Soldado F, Filipone L. Magnetic resonance imaging and clinical findings before and after tendon transfers about the shoulder in children with residual brachial plexus birth palsy: a 3-year follow-up study. *J Pediatr Orthop*. 2010;30(2):154-160. doi:10.1097/BPO.0b013e3181cfce09.

16. Cohen G, Rampal V, Aubart-Cohen F, Seringe R, Wicart P. Brachial plexus birth palsy shoulder deformity treatment using subscapularis release combined to tendons transfer. *Orthop Traumatol Surg Res*. 2010;96(4):334-339. doi:10.1016/j.otsr.2010.02.004.

17. Ozben H, Atalar AC, Bilsel K, Demirhan M. Transfer of latissmus dorsi and teres major tendons without subscapularis release for the treatment of obstetrical brachial plexus palsy sequela. *J Shoulder Elb Surg*. 2011;20(8):1265-1274. doi:10.1016/j.jse.2011.01.004.

18. Waters PM, Bae DS. Effect of tendon transfers and extra-articular soft-tissue balancing on glenohumeral development in brachial plexus birth palsy. *J Bone Joint Surg Am*. 2005;87(2):320-325. doi:10.2106/JBJS.C.01614.

19. Nixon M, Trail I. Management of shoulder problems following obstetric brachial plexus injury. *Shoulder Elb*. 2013:no-no. doi:10.1111/sae.12003.

20. Greenhill DA, Smith WR, Ramsey FV, Kozin SH, Zlotolow DA. Double Versus Single Tendon Transfers to Improve Shoulder Function in Brachial Plexus Birth Palsy. *J Pediatr Orthop*. 2017;00(00):1. doi:10.1097/BPO.0000000000000965.

21. Abzug JM, Kozin SH, Waters PM. Open Glenohumeral Joint Reduction and Latissimus Dorsi and Teres Major Tendon Transfers for Infants and Children

Following Brachial Plexus Birth Palsy. *Tech Hand Up Extrem Surg*. 2017;21(2):30-36.

22. Abzug JM, Kozin SH. Current Concepts: Neonatal Brachial Plexus Palsy. *Orthopedics*. 2010;33(6):430-435. doi:10.3928/01477447-20100429-25.

23. Hogendoorn S, van Overvest KL, Watt I, Duijsens AH, Nelissen RG. Structural changes in muscle and glenohumeral joint deformity in neonatal brachial plexus palsy. *JBone Jt SurgAm*. 2010;92(4):935-942. doi:10.2106/JBJS.I.00193.

24. Soldado F, Fontecha CG, Marotta M, et al. The role of muscle imbalance in the pathogenesis of shoulder contracture after neonatal brachial plexus palsy: A study in a rat model. *J Shoulder Elb Surg*. 2014;23(7):1003-1009. doi:10.1016/j.jse.2013.09.031.

25. Vitringa VMVG, Sluijs JA Van Der, Noort A Van, Royen BJ Van. Degree of Contracture Related to Residual Muscle Shoulder Strength in Children with Obstetric Brachial Plexus Lesions. *J Brachial Plex Peripher Nerve Inj*. 2015;10:23-29.

26. Nikolaou S, Peterson E, Kim A, Wylie C, Cornwall R. Impaired growth of denervated muscle contributes to contracture formation following neonatal brachial plexus injury. *J Bone Jt Surg*. 2011;93(5):461-470. doi:10.2106/JBJS.J.00943.

27. Nikolaou S, Ms LH, Cornwall R. Afferent Innervation, Muscle Spindles, and Contractures Following Neonatal Brachial Plexus Injury in a Mouse Model. *J Hand Surg Am*. 2015;40(10):2007-2016. doi:10.1016/j.jhsa.2015.07.008.

28. Cheng W, Cornwall R, Crouch DL, Li Z, Saul KR. Contributions of Muscle Imbalance and Impaired Growth to Postural and Osseous Shoulder Deformity Following Brachial Plexus Birth Palsy: A Computational Simulation Analysis. *J Hand Surg Am*. 2015;40(6):1170-1176. doi:10.1016/j.jhsa.2015.02.025.

29. Hale HB, Bae DS, Waters PM. Current Concepts in the Management of Brachial Plexus Birth Palsy. *J Hand Surg Am*. 2010;35(2):322-331. doi:10.1016/j.jhsa.2009.11.026.

30. Pondaag W, Malessy MJA, Van Dijk JG, Thomeer RTW. Natural history of obstetric brachial plexus palsy: a systematic review. *Dev Med Child Neurol*. 2004;46(Table I):138-144. doi:10.1111/j.1469-8749.2004.tb00463.x.

31. Pearl ML, Woolwine S, van de Bunt F, Merton G, Burchette R. Geometry of the

proximal humeral articular surface inyoung children: A study to define normal and analyze the dysplasia due to brachial plexus birth palsy. *J Shoulder Elb Surg*. 2013;22(9):1274-1284. doi:10.1016/j.jse.2012.12.031.

32. Donohue KW, Little KJ, Gaughan JP, Kozin SH, Norton BD, Zlotolow DA. Comparison of Ultrasound and MRI for the Diagnosis of Glenohumeral Dysplasia in Brachial Plexus Birth Palsy. *J Bone Joint Surg Am*. 2017;99(2):123-132. doi:10.2106/JBJS.15.01116.

33. Reading BD, Laor T, Salisbury SR, Lippert WC, Cornwall R. Quantification of humeral head deformity following neonatal brachial plexus palsy. *J Bone Jt Surg - Ser A*. 2012;94(18):1-8. doi:10.2106/JBJS.K.00540.

34. Greenhill DA, Trionfo A, Ramsey F V., Kozin SH, Zlotolow DA. Postoperative Loss of Midline Function in Brachial Plexus Birth Palsy. *J Hand Surg Am*. 2018:1-10. doi:10.1016/j.jhsa.2017.10.041.

35. Hoffer MM, Phipps GJ. Closed Reduction and Tendon Transfer for Treatment of Dislocation of the Glenohumeral Joint Secondary to Brachial Plexus Birth Palsy *. *J Bone Jt Surg*. 1998;80(7):997-1001.

36. Pearl ML, Edgerton BW, Kazimiroff P a, Burchette RJ, Wong K. Arthroscopic release and latissimus dorsi transfer for shoulder internal rotation contractures and glenohumeral deformity secondary to brachial plexus birth palsy. *J Bone Joint Surg Am*. 2006;88(3):564-574. doi:10.2106/JBJS.D.02872.

37. Russo SA, Kozin SH, Zlotolow DA, Nicholson KF, Richards JG. Motion Necessary to Achieve Mallet Internal Rotation Positions in Children With Brachial Plexus Birth Palsy. *J Pediatr Orthop*. 2017;00(00):1. doi:10.1097/BPO.0000000000001010.

38. Russo SA, Kozin SH, Zlotolow DA, et al. Scapulothoracic and glenohumeral contributions to motion in children with brachial plexus birth palsy. *J Shoulder Elb Surg*. 2014;23(3):327-338. doi:10.1016/j.jse.2013.06.023.

39. Russo SA, Loeffler BJ, Zlotolow DA, et al. Limited Glenohumeral Cross-body Adduction in Children With Brachial Plexus Birth Palsy : A Contributor to Scapular Winging. *J Pediatr Orthop*. 2014;00(00):1-6. doi:10.1097/BPO.0000000000000242.

40. Abzug JM, Chafetz RS, Gaughan JP, Ashworth S, Kozin SH. Shoulder Function After Medial Approach and Derotational Humeral Osteotomy in Patients With Brachial Plexus Birth Palsy. *J Pediatr Orthop*. 2010;30(5):469-474. doi:10.1097/BPO.0b013e3181df8604.

41. Russo SA, Zlotolow DA, Chafetz RS, et al. Efficacy of 3 therapeutic taping configurations for children with brachial plexus birth palsy. *J Hand Ther*. 2017:31-34. doi:10.1016/j.jht.2017.03.001.

42. Rapp EA, Richardson RT, Russo SA, Rose WC, Richards JG. A comparison of two non-invasive methods for measuring scapular orientation in functional positions. *J Biomech*. 2017;61:269-274. doi:10.1016/j.jbiomech.2017.07.032.

43. Wu G, Van Der Helm FCT, Veeger HEJ, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. *J Biomech*. 2005;38(5):981-992. doi:10.1016/j.jbiomech.2004.05.042.

44. Russo SA, Killelea CM, Zlotolow DA, et al. Scapular Stabilization Limits Glenohumeral Stretching in Children With Brachial Plexus Injuries. *J Hand Surg Am*. 2018:1-9. doi:10.1016/j.jhsa.2018.04.025.

45. Russo SA, Rodriguez LM, Kozin SH, et al. Therapeutic Taping for Scapular Stabilization in Children With Brachial Plexus Birth Palsy. *Am J Occup Ther*. 2016;70(5).

46. Pearl ML, Harris SL, Lippitt SB, Sidles JA, Harryman DT, Matsen FA. A system for describing positions of the humerus relative to the thorax and its use in the presentation of several functionally important arm positions. *J Shoulder Elb Surg*. 1992;1(2):113-118.

47. Pearl ML. Humeroscapular positions in a shoulder range-of-motion-examination. *J Shoulder Elb Surg*. 1992;1(6):296-305.

48. Pagnotta A, Haerle M, Gilbert A. Long-term Results on Abduction and External Rotation of the Shoulder after Latissimus Dorsi Transfer for Sequelae. *Clin Orthop Relat Res*. 2004;(426):199-205. doi:10.1097/01.blo.0000138957.11939.70.

49. Abdel-Ghani H, Hamdy KA, Basha N, Tarraf YN. Tendon transfer for treatment of internal rotation contracture of the shoulder in brachial plexus birth palsy. *J Hand Surg Eur Vol*. 2012;37(8):781-786. doi:10.1177/1753193412451401.

50. Al-Qattan MM. Latissimus dorsi transfer for external rotation weakness of the shoulder in obstetric brachial plexus palsy. *J Hand Surg Am*. 2003;28 B(5):487-490. doi:10.1016/S0266-7681(02)00393-5.

51. Kozin SH, Boardman MJ, Chafetz RS, Williams GR, Hanlon A. Arthroscopic treatment of internal rotation contracture and glenohumeral dysplasia in children with brachial plexus birth palsy. *J Shoulder Elb Surg*. 2010;19(1):102-110.

doi:10.1016/j.jse.2009.05.011.

52. Phipps GJ, Hoffer MM. Latissimus dorsi and teres major transfer to rotator cuff for Erb's palsy. *J Shoulder Elb Surg*. 1995;4(2):124-129. doi:10.1016/S1058-2746(05)80066-7.

53. Greenhill DA, Wissinger K, Trionfo A, Solarz M, Kozin SH, Zlotolow DA. External Rotation Predicts Outcomes after Closed Glenohumeral Joint Reduction with Botulinum Toxin Type A in Brachial Plexus Birth Palsy. *J Pediatr Orthop*. 2018;38(1):32-37. doi:10.1097/BPO.0000000000000735.

54. Kany J, Kumar HA, Amaravathi RS, et al. A subscapularis-preserving arthroscopic release of capsule in the treatment of internal rotation contracture of shoulder in Erb's palsy (SPARC procedure). *J Pediatr Orthop Part B*. 2012;21(5):469-473. doi:10.1097/BPB.0b013e328353a19f.

Appendix A

PATIENT DEMOGRAPHICS AND SURGICAL HISTORIES

Table 12 Patient demographics and surgical histories

		Total	Tendon Transfer	
			Single	Double
Age		6.0 ±1.9	6 ± 1.9	5.9 ±2.0
Sex		8 M, 18 F	4 M, 9 F	4 M, 9 F
Age at surgery		1.8 ±1.2	2.0 ± 1.3	1.6 ±1.1
Affected Arm	Right	13	7	6
	Left	13	6	7
Shoulder joint reduction				
	Open	20	10	10
	Closed	6	3	3
Subscapularis release/elevation		7	5	2
Prior closed shoulder reduction		4	2	2
Prior Botox to internal rotators		10	7	3
Prior nerve surgery (grafting)		1	1	0
Unable to reach midline		6	3	3
Subsequent de-rotational humeral osteotomy		2	0	2

Appendix B

PRE AND POSTOPERATIVE MODIFIED MALLET SCORES

Table 13 Pre and postoperative modified Mallet scores

	Preoperative scores				Postoperative scores			
	Single (N= 10)		Double (N = 11)		Single (N= 13)		Double (N = 13)	
Abduction	4.0	(± 0.0)	3.6	(± 0.5)	4.5	(± 0.5)	4.3	(± 0.5)
External Rotation	2.5	(± 0.7)	2.3	(± 0.7)	3.5	(± 0.7)	3.5	(± 0.7)
Hand-to-Neck	2.1	(± 0.3)	2.1	(± 0.3)	2.9	(± 0.9)	2.8	(± 0.9)
Hand-to-Spine	2.0	(± 0.0)	2.0	(± 0.0)	2.0	(± 0.0)	2.0	(± 0.0)
Hand-to-Mouth	2.4	(± 0.7)	2.1	(± 0.3)	3.2	(± 0.8)	2.6	(± 0.9)
Hand-to-Belly	3.8	(± 0.7)	4.0	(± 0.0)	2.8	(± 0.4)	3.1	(± 0.8)
Total	16.9	(± 1.1)	16.0	(± 1.3)	18.5	(± 1.8)	18.2	(± 1.7)

Appendix C

CHANGE IN MALLET SCORES

Table 14 Change in Mallet scores

	Single	Double
Abduction	0.5	0.7
External Rotation	1.0	1.2
Hand-to-Neck	0.8	0.7
Hand-to-Spine	0.0	0.0
Hand-to-Mouth	0.8	0.5
Hand-to-Belly	-1.0	-0.9
	1.6	2.2

Appendix D

JOINT ADDUCTION ANGLES

Table 15 Joint Adduction angles

Neutral	ST		GH		HT	
Single	49.2	(± 6.0)	24.7	(± 13.9)	59.8	(± 17.9)
Double	45.2	(± 8.0)	19.6	(± 8.7)	50.8	(± 13.0)
Abduction	ST		GH		HT	
Single	51.4	(± 16.5)	14.0	(± 13.5)	62.2	(± 14.6)
Double	50.7	(± 18.6)	5.3	(± 10.7)	52.9	(± 13.8)
External Rotation						
Single	47.5	(± 12.3)	5.5	(± 17.9)	51.0	(± 17.8)
Double	41.0	(± 13.9)	8.5	(± 18.5)	42.8	(± 26.7)
Internal Rotation						
Single	49.6	(± 9.8)	16.6	(± 17.9)	56.3	(± 16.8)
Double	47.3	(± 8.1)	12.2	(± 8.0)	47.5	(± 16.2)

Appendix E

INSTITUTIONAL REVIEW BOARD APPROVAL DOCUMENTS

WIRB
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Certificate of Action

Investigator Name: Ross Chafetz, PhD, PT, DPT	**Board Action Date:** 10/18/2018
Investigator Address: 3551 N. Broad St Philadelphia, PA 19140, United States	**Approval Expires:** 10/18/2019 **Continuing Review Frequency:** Annually
Sponsor: Shriners Hospitals for Children **Institution Tracking Number:** PHL1815	**Sponsor Protocol Number:** PHL1815 **Amended Sponsor Protocol Number:**
Study Number: 1247476	**IRB Tracking Number:** 20182511
Work Order Number: 6-1116520-1	**Panel:** 3
Protocol Title: Scapulothoracic and Glenohumeral Kinematics in Single versus Double Tendon Transfer in Brachial Plexus Birth Injury	

THE FOLLOWING ITEMS ARE APPROVED:
Investigator
Patient History Form #22831572.0 - As Submitted
Phone Script #22831573.0 - As Submitted
Protocol (09-14-2018)
Assent Information Sheet [IN0]
Consent Form [IN0]

Please note the following information:
WAIVECON - For the two retrospective research cohorts ("Source 1" and "Source 2), the Board found that this research meets the requirements for a waiver of consent under 45 CFR 46.116(d). Subjects in the third cohort, "Source 3", must sign the consent form(s) specified in this approval.

THE IRB HAS APPROVED THE FOLLOWING LOCATIONS TO BE USED IN THE RESEARCH:
Shriners Hospitals for Children - Philadelphia, 3551 N. Broad Street, Philadelphia, Pennsylvania 19140

ALL IRB APPROVED INVESTIGATORS MUST COMPLY WITH THE FOLLOWING:
As a requirement of IRB approval, the investigators conducting this research will:

- Comply with all requirements and determinations of the IRB.
- Protect the rights, safety, and welfare of subjects involved in the research.
- Personally conduct or supervise the research.
- Conduct the research in accordance with the relevant current protocol approved by the IRB.
- Ensure that there are adequate resources to carry out the research safely.
- Ensure that research staff are qualified to perform procedures and duties assigned to them during the research.
- Submit proposed modifications to the IRB prior to their implementation.
    - Not make modifications to the research without prior IRB review and approval unless necessary to eliminate apparent immediate hazards to subjects.
- Submit continuing review reports when requested by the IRB.
- Submit a closure form to close research (end the IRB's oversight) when:
    - The protocol is permanently closed to enrollment
    - All subjects have completed all protocol related interventions and interactions
    - For research subject to federal oversight other than FDA:
        - No additional identifiable private information about the subjects is being obtained
        - Analysis of private identifiable information is completed
- If research approval expires, stop all research activities and immediately contact the IRB.

This is to certify that the information contained herein is true and correct as reflected in the records of this IRB. WE CERTIFY THAT THIS IRB IS IN FULL COMPLIANCE WITH GOOD CLINICAL PRACTICES AS DEFINED UNDER THE U.S. FOOD AND DRUG ADMINISTRATION (FDA) REGULATIONS, U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES (HHS) REGULATIONS, AND THE INTERNATIONAL CONFERENCE ON HARMONISATION (ICH) GUIDELINES.

Board Action: 10/18/2018