



# The Elongation of Biceps Muscle Tendon Unit After Rerouting of the Long Head of Biceps Tendon as Superior Capsular Augmentation: A Quantitative Measurement

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**Purpose:** The purpose of this study was to investigate the elongation of the biceps muscle tendon unit after rerouting of the long head of the biceps tendon without transection, with and without release of the transverse humeral ligament in a 3-dimensional model. **Methods:** A total of 60 sets of computed tomography images of shoulders were acquired, and a point-cloud model was generated after 3-dimensional reconstruction. Simulation of rerouting of the long head of the biceps tendon was performed by assuming that the long head of the biceps tendon travels to the center of the greater tuberosity from the supraglenoid tubercle and then back to the bicipital groove distally, with or without the release of the transverse humeral ligament. The elongation of the biceps muscle tendon unit by both manners was measured and correlated with age, height, weight, body mass index, gender, and hand dominance. **Results:** The mean length of the long head of the biceps tendon is  $74.22 \pm 3.06$  mm, and the length is significantly longer, at  $112.23 \pm 4.92$  mm ( $P = 0.0002$ ) and  $96.47 \pm 2.58$  mm ( $P = 0.0004$ ). The absolute elongation of the biceps muscle tendon unit after rerouting of the long head of the biceps tendon, without or with transverse humeral ligament release, showed significant differences, which were  $38.73 \pm 3.03$  mm and  $22.28 \pm 3.25$  mm, respectively ( $P = 0.0008$ ). No significant correlations were observed between the amount of the elongation and the subject's age, height, weight, or body mass index. No significant difference was observed in the amount of the elongation between differing gender and hand dominance. **Conclusions:** Rerouting of the long head of the biceps tendon resulted in significant elongation of the biceps muscle tendon unit. Release of the transverse humeral ligament partially decreased this elongation. **Clinical Relevance:** Rerouting of the long head of the biceps tendon may lead to overtension of the biceps. If it is adopted in clinical use, transverse humeral ligament release is recommended.

**M**assive rotator cuff tears are common pathologies that affect the aging population by causing pain and weakness of the shoulder that compromise daily function.<sup>1,2</sup> For chronic cases with delayed presentation, severe tendon retraction and fatty infiltration in

muscle will decrease the likelihood of full repair of the tendon.<sup>3,4</sup> To address this problem, multiple techniques have been proposed in the literature, including partial repair, tenotomy of the long head of the biceps, latissimus dorsi tendon transfer, and reverse total shoulder arthroplasty.<sup>5-9</sup> Recently, several studies have indicated a paramount role of the superior capsule of the glenohumeral joint in stabilization of the joint, which has been shown to be disrupted in the pathology of irreparable rotator cuff tear.<sup>10</sup> Reconstruction of the superior capsule of the glenohumeral joint, which has been suggested to restore its role in balancing the superior migration of the humeral head and maintaining the acromiohumeral distance, has been proven to be a promising technique for the management of irreparable rotator cuff tear.<sup>11</sup>

Among all the grafts used for superior capsule reconstruction, the long head of the biceps tendon (LHBT) has gained increased popularity because of the

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convenience of obtaining it, the lack of immune rejection, easier surgery, lower expenses, and favorable short to intermediate clinical outcome.<sup>12-14</sup> However, it is still debated whether to perform tenodesis of the proximal part of biceps tendon with tenotomy of distal part or just to reroute the tendon laterally, with preservation of its continuity. It has been reported that biceps tenotomy is associated with cosmetic deformity, cramping or weakness, while maintaining the continuity of LHBT along with the muscle belly will preserve the vascularity to the tendon, which would facilitate healing.<sup>12,15</sup> But others may have a consideration about the elongation of the biceps muscle tendon unit after rerouting, which potentially leads to an increase in the tension and anchor pullout.<sup>12,16</sup>

The purpose of this study was to investigate the elongation of the biceps muscle tendon unit after LHBT rerouting with and without release of the transverse humeral ligament in a 3-dimensional (3D) model. We hypothesized that the rerouting of the LHBT would result in significant elongation of the biceps muscle tendon unit and that release of the transverse humeral ligament could partially decrease the elongation.

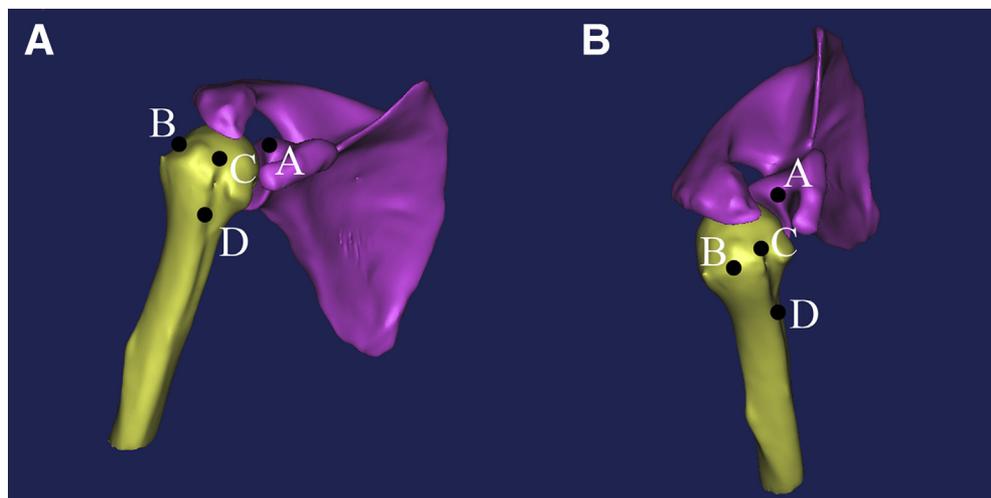
## Methods

### 3-D Computed Tomography Model Reconstruction and Identification of the Landmarks for LHBT Rerouting

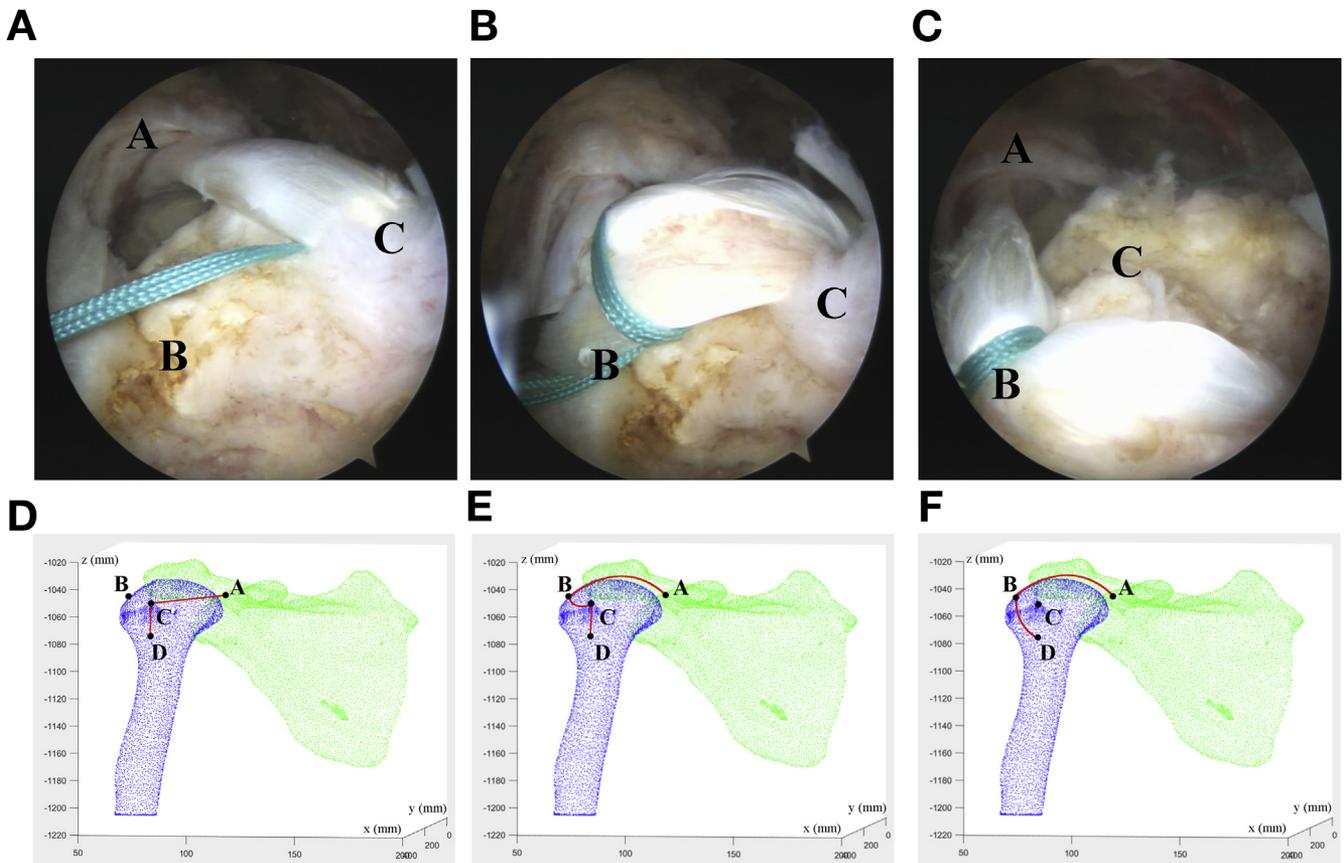
The study was approved by the institutional review board, and informed consent was obtained from each patient. Computed tomography (CT) scan images (Aquilion 64, Toshiba America Medical Systems, Tustin, CA, USA) were obtained from a total of 60 patients (35 female and 25 male, 37 right shoulder and 23 left

shoulder) between January 2015 and October 2019. The mean age of patients enrolled was 66 years (range 54–73 years), and all the patients were right-handed. Inclusion criteria were patients with massive rotator cuff tear without bony changes evidenced by CT. Exclusion criteria included patients with fracture or deformity in the scapula or proximal humerus.

In our study, the standard 120 kVp and 200 mA bone-reconstruction sequence was employed, with the parameters set at a slice thickness of 0.8 mm and a resolution of  $512 \times 512$  pixels. The upper arm was immobilized in neutral position during scanning. The 3-D model of the scapula and proximal humerus was reconstructed from the CT images using commercial 3-D reconstruction software (Mimics, Materialise, Leuven, Belgium) (Fig 1). To measure the length and elongation of the biceps muscle tendon unit, 4 anatomic landmarks were identified on the model, including the supraglenoid tubercle, the center of greater tuberosity, the superior margin of intertubercular groove, and the inferior margin of the intertubercular groove. The supraglenoid tubercle was marked, with the most prominent point at the supraglenoid tubercle, while the center of greater tuberosity was identified as the midpoint of the lateral margin of the footprint on the greater tuberosity. The superior margin of the intertubercular groove was identified as a point at the level of the lesser tuberosity within the groove, while the inferior margin of intertubercular groove was marked as a point within the groove and 52 mm below the top of the humeral head, which is the superior insertion of pectoralis major<sup>17</sup> (Fig 1). For each of the anatomic landmarks, coordinates in the 3-D frame ( $x, y, z$ ) were recorded for subsequent analysis. The model was independently viewed and marked by 2 sports medicine surgeons (CJ, HZ) on 2 separate occasions at a mean of 3 weeks apart.



**Fig 1.** Illustration of the anatomic landmarks for LHBT rerouting on right shoulder 3-D model of the glenoid and the proximal humerus and illustration of the anatomic landmarks for LHBT rerouting. (A) 3-D contour of the glenoid and the proximal humerus was illustrated. (B) Bird's-eye view is employed to show the footprint of supraspinatus and infraspinatus on greater tuberosity. A, supraglenoid tubercle; B, the center of greater tuberosity; C, the entrance into intertubercular groove; D, the expected most superior insertion of pectoralis major. (LHBT, long head of biceps tendon.)



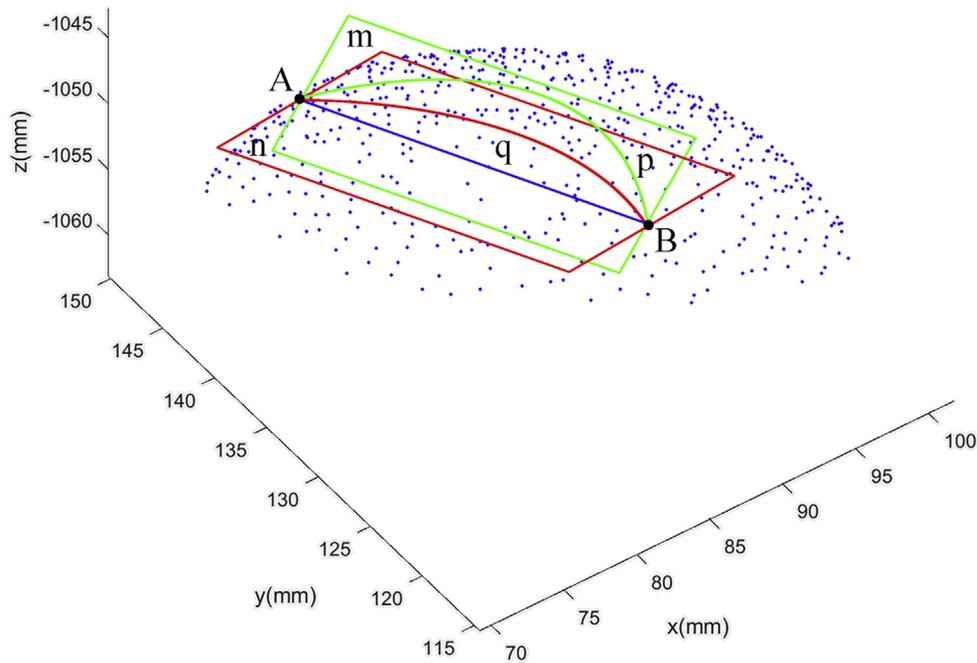
**Fig 2.** Intraoperative view and simulation of LHBt rerouting of right shoulder. (A, D) Original path of LHBt from supraglenoid tubercle via entrance into intertubercular groove to the level of the insertion of pectoralis major. This was the sum of length of arc AC and CD. (B, E) Rerouting of LHBt to greater tuberosity without release of transverse humeral ligament. The path of LHBt went from supraglenoid tubercle to the midpoint of the lateral margin of the footprint of greater tuberosity and then went back to the entrance into the intertubercular groove until the level of the insertion of the pectoralis major. This was the sum of length of arc AB, BC and CD. (C, F) Rerouting of LHBt with transverse humeral ligament. The path of LHBt was from supraglenoid tubercle to the midpoint of the lateral margin of the footprint of the greater tuberosity and was then directly aimed to the level of the insertion of the pectoralis major. This was the sum of length of arc AB and BD. A, supraglenoid tubercle; B, the center of greater tuberosity; C, the entrance into intertubercular groove; D, the expected most superior insertion of pectoralis major. (LHBt, long head of biceps tendon.)

### 3-D Point-cloud Model Generation and Simulation of LHBt Rerouting

The reconstructed 3-D model of the glenoid and proximal humerus associated with the identified anatomic landmarks was exported in the format of a point-cloud pattern and then imported into MatLab software (Mathworks, Natick, MA, USA) to generate the point-cloud model for the following analysis. The radius of the humeral head was determined by fitting the humeral head using the best-fit sphere.

To simulate the rerouting of the LHBt, 3 conditions were tested. First, the original path of the LHBt was marked; it led from the supraglenoid tubercle to the entrance of the bicipital groove and through the intertubercular groove to the level of the expected, most superior insertion of the pectoralis major, where it was regarded as the constant landmark for subsequent comparison (Fig 2A, D). Second, to use the autologous

LHBt for superior capsule reconstruction, it was rerouted to the center of the greater tuberosity to restore a full coverage by the supraspinatus. Then it went back to the entrance into the intertubercular groove until the level of the expected most superior insertion of the pectoralis major (Fig 2B, E). Third, if transverse humeral ligament release was further performed, the path of the LHBt would travel directly to the level of the expected most superior insertion of the pectoralis major after leaving the greater tuberosity without going through the intertubercular groove (Fig 2C, F). The length of the LHBt was defined as the total length from the supraglenoid tubercle to the level of the expected most superior insertion of the pectoralis major via various courses. The length of the LHBt under each setting was measured, and the elongation of the biceps muscle tendon unit after the rerouting was compared.



**Fig 3.** Measurement of the 3-D distance between 2 points on an irregular surface. Point A and B are 2 points on an irregular surface (blue dots) with a line passing A and B (blue line). To illustrate the algorithm for calculation of the 3-D distance between point A and B, a set of planes passing line AB with an angular increment of  $5^\circ$  is created. Here only 2 planes, m and n, were drawn for demonstration. Planes m and n intersect the irregular surface separately and produce a curve, p and q. The length of each curve is calculated, and the smallest value is adopted as the 3-D distance between points A and B on the surface.

### Measurement of the 3-D Distance Between Two Points on an Irregular Surface

A key step in the calculation of the length of the LHBT in differing settings is to measure accurately the distance between 2 points on an irregular surface in a 3-D frame. In this study, a least-distance algorithm was developed with the principle of calculus of variation. Basically, set points A and B (blue dots in Fig 3) are 2 points on an irregular surface, with a line passing A and B. A set of planes passing line AB with an angular increment of  $5^\circ$  is created, and each plane produces a curve by intersection with the surface. The length of each curve is calculated, and the smallest value is adopted as the 3-D distance between 2 points on the surface (Fig 3).

### Statistical Analysis

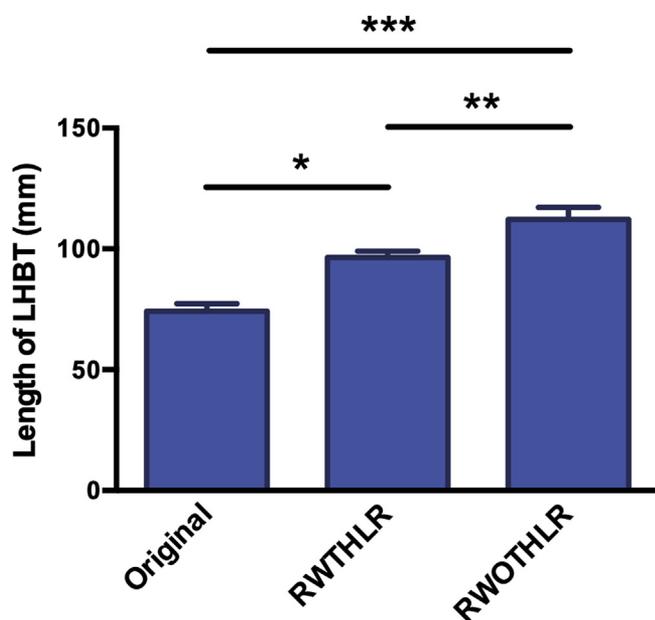
All the data are expressed as the mean and standard deviation. Shapiro-Wilk tests were performed to check normality of all variables. The values of elongation of the biceps muscle tendon unit in differing settings were compared and examined using the paired-samples Student *t* test. Spearman rank correlation tests were used to investigate the relationship between the elongation of the biceps muscle tendon unit without or with transverse humeral ligament release and the demographic factors, including age, height, weight, and body mass index (BMI). The Student *t* test was used to evaluate the difference in the elongation, without or with transverse humeral ligament release regarding gender and hand dominance. The intraobserver reliability and interobserver reliability of the identified

coordinates of the anatomic landmarks were evaluated by intraclass correlation coefficients (ICCs), which were classified as excellent (ICC > 0.75), good (ICC 0.60-0.74), fair (ICC 0.40-0.59), or poor (ICC < 0.40).<sup>18</sup> Significant difference was considered when the *P* value was less than 0.05. A sample size of 60 patients was adequate to achieve 80% power regarding the comparison.

### Results

The mean length of the LHBT from the supraglenoid tubercle to the expected superior-most insertion of pectoralis major is  $74.22 \pm 3.06$  mm, while the length is significantly increased to  $112.23 \pm 4.92$  mm ( $P = 0.0002$ ) and  $96.47 \pm 2.58$  mm ( $P = 0.0004$ ) after rerouting to the greater tuberosity without or with transverse humeral ligament release (Fig 4). The absolute elongation of the biceps muscle tendon unit after rerouting of the LHBT, without or with transverse humeral ligament release, showed significant difference:  $38.73 \pm 3.03$  mm and  $22.28 \pm 3.25$  mm, respectively ( $P = 0.0008$ ) (Fig 4).

Significant correlation was obtained between the amount of the elongation and the radius of the humeral head, whereas no significance was observed between the amount of the elongation and the subject's age, height, weight, or BMI (for simulation without release of transverse humeral ligament, correlation with radius of humeral head:  $\rho = 0.54$ ,  $P = 0.0007$ ; age:  $\rho = 0.08$ ,  $P = 0.15$ ; height:  $\rho = 0.17$ ,  $P = 0.35$ ; weight:  $\rho = 0.32$ ,  $P = 0.47$ ; BMI,  $\rho = 0.27$ ,  $P = 0.24$ ;



**Fig 4.** The length of the LHB before and after rerouting. The figure shows the length of the LHB before and after the rerouting. (LHB, long head of biceps tendon; RWOTHLR, rerouting without transverse humeral ligament release; RWTHLR, rerouting with transverse humeral ligament release.) \*, 0.0007; \*\*, 0.0004; \*\*\*, 0.0002.

for simulation with release of the transverse humeral ligament, correlation with the radius of the humeral head:  $\rho = 0.22$ ,  $P = 0.001$ ; age:  $\rho = 0.13$ ,  $P = 0.25$ ; height:  $\rho = 0.37$ ,  $P = 0.35$ ; weight:  $\rho = 0.48$ ,  $P = 0.17$ ; BMI,  $\rho = 0.44$ ,  $P = 0.34$ ). No significant difference was observed in the amount of the elongation between different genders and hand dominance (for simulation without release of transverse humeral ligament, gender:  $P = 0.27$ ; hand dominance:  $P = 0.32$ ; for simulation with release of transverse humeral ligament, gender:  $P = 0.45$ ; hand dominance:  $P = 0.13$ ).

Physicians' agreement in identification of the anatomic landmarks between the 2 views of the same patient was excellent, with an ICC ranging from 0.78 to 0.91 ( $P = 0.0007$ ). The agreement in identification of the anatomic landmarks among various physicians was excellent, with an ICC ranging from 0.71 to 0.84 ( $P = 0.0008$ ).

## Discussion

Rerouting of the LHB would result in significant elongation of the biceps muscle tendon unit, and release of the transverse humeral ligament could partially decrease the elongation.

Surgical treatment of massive rotator cuff tear remains a challenge for shoulder surgeons. Various techniques have been tried so as to improve the clinical outcome. Recently, superior capsular reconstruction was reported to be an effective treatment for massive rotator cuff tear

by recentering the humeral head to prevent superior migration.<sup>1,10</sup> Mihata and colleagues' result suggested an improvement in pain, range of motion and strength in their short-term follow-up study.<sup>10</sup> Several graft resources have been suggested for the reconstruction of the superior capsule. In Mihata et al.'s original research, they used fascia lata autograft.<sup>10</sup> Although fascia lata harvest is a simple procedure, it may result in addition donor-site morbidity, such as pain on walking, scarring, scar sensitivity, hematoma, muscle herniation, and wound infection.<sup>19,20</sup> To avoid the possible donor-site morbidity, some authors have proposed human acellular dermal allograft as an alternative.<sup>14,21</sup> Despite the growing popularity of use of this new material, the immune reaction and the price are major concerns in their application.<sup>22</sup> To avoid the above complication, the LHB was proposed as an excellent source because of the advantage of natural available tissue, reduced cost, a less technically demanding procedure, and no donor-site comorbidity.<sup>1,22</sup>

Even though the application of the LHB as a source of superior capsular reconstruction has gained popularity in recent years, the exact procedure has not been agreed on.

First, where should the tendon fixation site be? In Lin's study, they inserted the anchor for fixation close to the entrance of intertubercular groove,<sup>13</sup> whereas Chillemi suggested that the point 5-10 mm lateral to the greater tuberosity was the best place.<sup>23</sup> A study performed by Kim used the point between footprint and cartilage as the fixation site.<sup>17</sup> In our study, we adopted the method developed by Hermanowicz, who believed that the center of the greater tuberosity resembled the anatomic insertion of the supraspinatus, which is the optimal location for anchor insertion.<sup>16</sup>

Second, should the continuity of the LHB be preserved? To date, little of the literature has focused on the comparison between LHB tenodesis and distal tenotomy with LHB rerouting. The reasons for preserving the continuity of the biceps originated from the benefits of the tendon biology because maintaining the integrity of the biceps would provide better blood supply and benefit the healing process. Moreover, the intact LHB may serve as a vascularized graft for the retracted supraspinatus and infraspinatus, which bridge the torn end to the greater tuberosity.<sup>16</sup>

Third, should the transverse humeral ligament be released? Prior studies have suggested that the transverse humeral ligament is a distinct structure covering the intertubercular groove, which is composed of the fibers of the subscapularis tendon, with contributions from the supraspinatus tendon and the coracohumeral ligament.<sup>24-27</sup> There may be concern about the risk of subscapularis tendon damage after transverse humeral ligament release. However, this procedure has been widely used in LHB tenodesis with excellent clinical outcomes.<sup>27,28</sup>

Regarding the consequence of elongation of the biceps muscle tendon unit, it has been reported that elongation of the biceps muscle tendon unit after distal biceps repair leads to various outcomes in the Disabilities of the Arm, Shoulder and Hand (DASH) score.<sup>29</sup> There have also been concerns about the increased tension caused by rerouting of the LHBT because over-tension of the biceps muscle tendon unit may lead to failure through anchor pullout or tendon rupture.<sup>30</sup> This is proved by our study. We found that rerouting of the LHBT would result in elongation of the biceps muscle tendon unit to an average of 3.9 cm. This over-tension of the biceps muscle tendon unit may cause clinical symptoms and put the fixation into high risk of failure.

Most of the procedure of LHBT tenodesis or rerouting requires release of the transverse humeral ligament to enable better visualization of the site for anchor insertion.<sup>12,16</sup> However, few investigations have been conducted to evaluate the role of releasing the transverse humeral ligament in the elongation of the biceps muscle tendon unit after rerouting of the LHBT in treatment of massive rotator cuff tears.<sup>16</sup> Our results suggested that release of the transverse humeral ligament would decrease the elongation of biceps muscle tendon unit, which may consequently reduce the tension of in the biceps after the procedure. The strength of our study is that, with the help of 3-D modeling, we were measuring the true 3-D distance between 2 points on an irregular surface. This made our result more accurate and reliable compared with simple 2-D measurement.

### Limitations

There are several limitations to our study. First, this study was performed on a 3-D reconstruction model from CT images instead of measurement in situ. However, because the course of the LHBT is just on the surface of the bone architecture, the thickness of soft tissue such as the periosteum was minimal. Second, our measurement was conducted when the shoulder was placed in 0° of abduction and neutral position, which is different from the posture in the beach-chair position or the lateral decubitus position intraoperatively. Third, internal or external rotation of the upper arm may result in changes in the position of the anatomic markers for the evaluation which, in turn, would have an effect on the final measurement. It was suggested that internal rotation would decrease the total length of the biceps muscle tendon unit, whereas external rotation would increase the overall length of the biceps muscle tendon unit. In this study, the upper arm was placed in a neutral position during the scanning so as to diminish the effect of rotation. Another limitation is that the anatomic landmarks for calculation were identified manually, which may bring in variation.

However, the reliability between the 2 independent observers was excellent. It was admitted that this study only quantitatively evaluated the elongation of the biceps muscle tendon unit in distance after rerouting, whereas soft-tissue deformation, collagen elasticity and tension generated after the elongation were not measured in this geometric model.

### Conclusions

Rerouting the LHBT resulted in significant elongation of the biceps muscle tendon unit. Release of the transverse humeral ligament partially decreased this elongation.

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