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# Musculotendon parameters estimation by ultrasound measurement and geometric modeling: application on brachialis muscle

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*Abstract*- Computational modeling for musculoskeletal system provides quantitative insights in analyzing human movement. One of the major challenges in neuromusculoskeletal modeling is to accurately estimate the musculotendon parameters on subject-specific basis. The ultrasound imaging technology presents a new approach to obtain the parameters in vivo. The pennation angle and fascicle length of brachialis (BRA) were measured in vivo with the use of ultrasonography to investigate the relationship between these muscle architecture parameters and elbow joint position. A generic interactive graphics-based geometrical model of the upper limb and BRA was developed to get the musculotendon length and moment arm of the muscle. The results indicate human brachialis architecture is significantly affected by changing of joint angle at passive horizontal movement. These in-vivo measurements provide subjects-specific information and these muscle parameters can be used to set up the neuromusculoskeletal model for the muscle force and torque estimation.

## I. INTRUDUCTION

Human pennate muscle architecture can be defined as the arrangement of muscle fibers within a muscle relative to its tendinous tissue [1]. Muscle architecture parameters include pennation angle (the acute angle between the line of action of the tendon and the line of the muscle fibers), muscle fibre length (the length of a small bundle of muscle fibers from the tendon of origin to the tendon of insertion) and muscle thickness (the distance between superficial and deep muscle aponeurosis, or superficial of muscle and muscle-bone boundary).

Information of muscle architecture is essential for the study of muscle functions since muscle architectural parameters have significant effects on the muscle's force generating capacity [2-3]. The muscle architectural parameters also can be used to set up the neuromusculoskeletal (NMS) model for investigating human movement [4]. Appropriate modeling can provide both qualitative and quantitative insights into the neuromusculoskeletal system and its motion dynamics [5]. The underlying muscle contraction and dynamics information could also be described by this approach, such as the force producing characteristics of the muscle and the individual muscle forces and moments during motor task [6]. Sensitivity and validation study showed that the accuracy of the estimated values of the musculotendon complex (MTC) parameters have significant effects on the modeling and simulation results [7-8]. Therefore, one of the major challenges in neuromusculoskeletal modeling is to accurately measure the musculotendon parameters.

Most previous studies were based on cadaver specimen [4, 9] and some investigators simply adopted the values reported in the earlier cadaver studies for their simulation in biomechanics studies [10].However, muscle in the embalmed cadavers have been reported to change their morphological characteristics due to shrinkage [11]. Moreover, muscle architecture could vary significantly among subjects. Therefore, it is necessary to obtain the parameters in vivo to acquire more precise information on the specific subjects. Medical imaging techniques have been used to get the parameters of musculoskeletal system in vivo recently, such as ultrasound (US) [12-14], computerized tomography (CT) and Magnetic Resonance Imaging (MRI) [15-16]. However, MRI or CT has the disadvantages such as high cost required, radiation exposure and limited access to instrument. Ultrasonography could reveal the fat, muscle or bone and is more convenient on repeated measurement compared to MRI or CT. The previous muscle architecture measurements using ultrasound were mainly performed on normal subjects or athletes to evaluate the muscle function [12-14]. Few reports were available on ultrasound measurements combined with musculoskeletal modeling to estimate musculotendon parameters.

Human brachialis muscle was measured in this study. This elbow flexor muscle has the largest PCSA in the muscle group of elbow flexors [17] and PCSA is considered the index of the force generation capacity of the muscle group [6]. Therefore, Brachialis is assumed to have large potential of force generation in elbow flexors and it is important to study the function of this muscle. Since Brachialis is a deep layer muscle and under the cover of biceps brachii, the electromyographic (EMG) measurement and electrophysiology study of brachialis must be tested through needle EMG, which is an invasive approach [4]. Ultrasonography can reveal the architecture of brachialis and study the muscle function non-invasively. In this study, geometric model of the muscle in the elbow joint was built and the relationship between the brachialis muscle architecture parameters and elbow joint angle at rest was studied based on the model and ultrasound imaging technology.

## II. METHOD

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### A. Musculoskeletal Modeling

A generic interactive graphics-based model of the upper limb and brachialis muscle was developed using SIMM (MusculoGraphics, USA). Software for Interactive Musculoskeletal Modeling (SIMM) is a powerful tool kit that facilitates the construction, modeling, animation, and analysis of three-dimensional musculoskeletal systems. Detailed description of the SIMM software could be found elsewhere [18].

The elbow joint was defined as a uniaxial hinge joint with its axis passing through the centers of the capitulum and trochlear sulcus [19]. Elbow range of motion was modeled from 0° to 90° flexion. The model defined the bone surfaces of the humerus, ulna, radius, hand, rib cage, scapula and clavicle. Each body segment is composed of polyhedra that describe the bone surfaces. Muscles are modeled as line segments connected with via points allowing the muscle to wrap around bones and joints. Brachialis muscle started in the middle of humerus, wrapped on a defined cylinder with two via points and ended in the head of ulna.

The muscle architecture parameters measured, which include the musculotendon length, muscle pennation angle, muscle fibre length and muscle thickness, were shown in Figure 1.

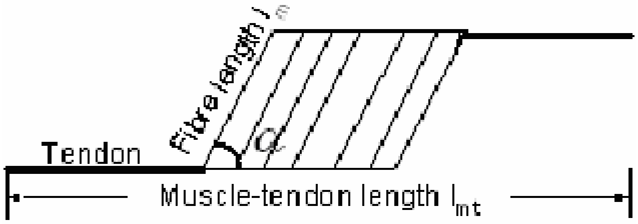

Fig1 Muscle architecture parameters measured in this study: Pennation angle(α); Muscle fibre length (Fascicle length)$l_m$; Muscle thickness(MT).

### B. Ultrasonography Measurement

A volunteer without physical disabilities (male, age 29 years) joined this preliminary study. This study was approved by the human ethical committee in The Hong Kong Polytechnic University. All the participants gave informed consent following the ethical procedures.

The major instruments used in the experiment included: a B-mode ultrasonography scanner with 7.5 MHz 38mm probe (Sonosite 180 Plux, Sonosite Inc., USA); a dynamometer (Cybex Norm Testing & Rehabilitation System, Cybex international Inc, USA); a mechanical 3-D digitizer (MicroScribe-3D, USA); and an assessment high-back chair with adjustable height. Prior to the tests, calibration was done on the digitizer, dynamometer and ultrasound probe. During the experiment, the subject was seated in the chair, with the dominative arm placed in a horizontal plane at the same height of the shoulder and the shoulder was in 90° abduction and 0° flexion. The forearm was placed in a supinated position. The elbow flexion-extension axis was aligned with the vertical axis of the dynamometer. During the test, the ultrasound probe was put on the anterior part of upper arm, 1cm proximal to the elbow joint. Coupling gel was applied to enhance US conduction between the US probe and skin surface. Typical ultrasonography of the brachialis, biceps brachii and biceps tendon was shown in Figure 2. The white fringe of the humerus bone and the dark muscle fascicle were observed in the ultrasonography image.

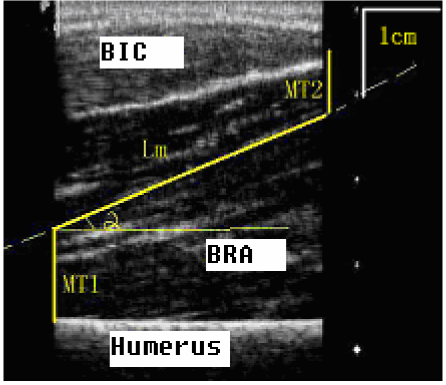

Fig2. Sonograph of the BRA muscle

Muscle origin and insertion points of the muscle were defined as the centroids of muscle attachment areas. Although anatomically these attachments are areas, for our purposes in modeling, the attachment site is assumed to be concentrated at a discrete point. The coordinates of those muscle attachment points were then digitized using the 3-D digitizer with respect to the corresponding skin surface middle point of the ultrasound probe in local coordinate systems.

Musculotendon length ($l_{mt}$) was determined by computing the sum of the lengths of the line segments on the muscle path using the following equation:

$$l_{mt} = \sum_{i=1}^{n-1} | P_{i+1} - P_i | \qquad (1)$$

where $P_1, P_2, \ldots, P_n$ are muscle attachment and via points.

Tendon length($l_T$) was calculated by subtracting muscle fibre length ($l_f$)from $l_{mt}$ , taking pennation angle (α) into account:

$$l_T = l_{mt} - l_f \cos\alpha. \qquad (2)$$

Muscle fibre length and pennation angle were estimated from ultrasound imaging (Fig 2). Pennation angle (α) could directly be measured in the image and the whole muscle fibre length ($L_f$) was estimated using a trigonometry method [20]:

$$L_f = L_m + MT_1 / \sin\alpha + MT_2 / \sin\alpha \qquad (3)$$

where $L_f$ is the whole estimated muscle fibre length, $L_m$ is the visible part of the muscle fibre, $MT_1$ and $MT_2$ are the distance of fibre distal end point to the superficial aponeurosis and the distance of fibre proximal end to the bone respectively, and α is the pennation angle. The subject was instructed to relax during the entire measurement. The measurement range was from full extension (0° flexion) to 90° flexion with 10° increment in each trail. Three trials were done for each position. Ultrasound image was analyzed off-line to find the muscle architecture parameters. The results were presented with the mean and standard deviation.

## III. RESULTS

At rest, pennation angle and fibre length of the brachialis muscle were found to be correlated with elbow joint angle. The relationship of the pennation angle (α) against the joint angle (θ) was fitted with a linear function ($\alpha = 0.17\theta+13.415.137; r^2=0.96$). The relationship of the muscle fibre length (Lf) against the joint angle (θ) was fitted with a quadratic function ($Lf=0.0007\theta^2-0.1016\theta+11.393$, $r^2=0.98$) (Figure 3). Figure 3 showed that pennation angle significantly increased from 13.6±0.6° (mean ±S.D.) to 26.7±1.6° when joint angle increased from 0° to 90° flexion. The results also showed Lf has obviously decreased from 11.7±0.5cm to 7.4±0.1cm from 0° to 90° elbow flexion

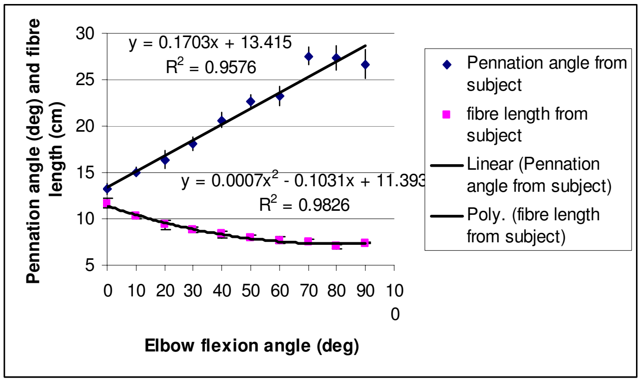

Fig.3 Normal subject's BRA muscle parameters as a function of elbow joint angle in passive condition

In the musculoskeletal model, the curve of $l_{mt}$ vs elbow joint angle was plotted in Figure 4.

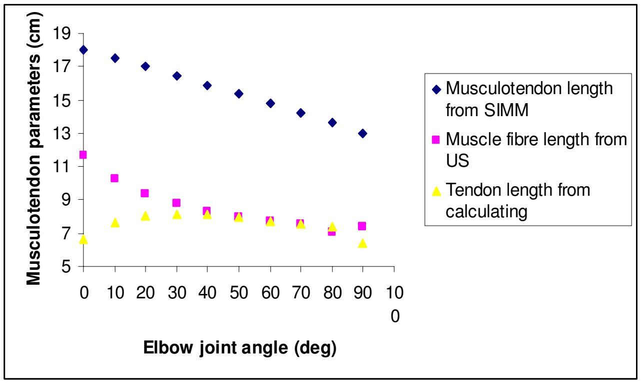

Fig4. Musculotendon parameters from modeling ($l_{mt}$), US measurement ($l_f$), and Calculating from (2) ($l_t$)

## IV. DISCUSSION

The ultrasonography measurement showed that the pennation angle and fibre length of the brachialis muscle was dependent on elbow joint angle in passive condition. This finding of brachialis muscle was similar to some of the previous in vivo studies on gastroncnemius, triceps surae, vastus lateralis and biceps femoris muscle skeletal muscle [12, 21-23]. All of these studies showed the muscle architecture parameters were related with joint angle at resting condition. However, the results in this study are different from those in Herbert et al.[13] for the brachialis with motion in vertical direction. This might be related to the effects of gravity, since the arm in our study was in horizontal plane without the gravitational effect with different joint angle.

Table 2 showed the data of brachialis muscle parameters of subject in this study and those in other studies reported in the literatures [24-28]. Attempts were made to validate the ultrasonography results with direct anatomical measurements and results showed no significant difference between ultrasound and direct measurements of the muscle parameters on cadaver [12, 23]. These studies showed that ultrasonography is an accepted method used to measure muscle parameters and would get similar results compared with directly measurement on cadavers. However, the studies of muscle architecture based on cadavers have limited the ability to determine functional implications in humans because of the use of older muscle and the limitation of describing the muscle architecture in the position of fixation. Martin et al. [29] compared the fibre length and pennation angle of human skeletal muscle such as Medial (MG) and lateral (LG) gastrocnemius in cadaver and live subjects. They found architectural characteristics of cadaver muscle differed from both relaxed and contracted in vivo muscle. Fukunaga et al.[22] found the architecture of actively contracting muscle fibres differ considerably that that which occurs when movement is passively induced. Therefore, the use of cadaver data in the study of architecture and modeling of muscle functions would result in accumulating errors in the results. The difference between the cadaver results and our in vivo data implied that ultrasound measurement can provide alterative method to collect the subject-specific data in vivo for biomechanics model in estimating the muscle function. In vivo studies can provide the muscle architecture changes both with joint angle and with the contractions.

Table 2

| Subject in this stud and Literature Cadaver | Pennation angle (°) Mean.(SD) | Muscle fibre length (cm) Mean(SD) |
|---|---|---|
| Normal subject (dominate side) | 21.1(5.3) | 8.6 (1.5) |
| Murray et al., (2000) | 0 | 9.9 (1.6) |
| Amis et al., (1979) | 0 | 12.3 |
| Winters (1988) | 15.0 | 9.11 |
| Lieber et al., (1992) | 2 (0.6) | 12.1(0.8) |
| Langenderfer et al., (2004) | 18.0 (6.0) | 8.7 (1.5) |

This study found that in-vivo ultrasonography combined with musculoskeletal modeling could be used to estimate muscle architectural parameters. The results showed that pennation angle and fibre length of brachialis are elbow joint angle dependent. These in-vivo measurements on muscle architecture provide subjects-specific information and allow the development of subject-specific models.

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