Characterization of Human Shoulder Joint Stiffness across 3D Arm Postures and its Sex Differences

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***Abstract*— Understanding the characteristics of shoulder joint stiffness can offer insights into how the shoulder joint contributes to arm stability and assists in various arm postures and movements. This study aims to characterize posture-dependent shoulder stiffness in a three-dimensional (3D) space and investigate its potential sex differences. A multi-degree-of-freedom, parallel-actuated shoulder exoskeleton robot was used' to perturb the participant's shoulder joint and measure the resulting torque responses while participants relaxed their shoulder muscles. The group average results of 40 healthy individuals (20 males and 20 females) revealed that arm postures significantly affect shoulder stiffness, particularly in postures involving shoulder flexion/extension and horizontal flexion/extension. Shoulder stiffness consistently increased as the shoulder flexion angle decreased and the shoulder horizontal flexion/extension approached the limit of its range of motion. The comparative group results between males and females indicated that shoulder stiffness in males was greater than that in females across all 15 arm postures measured in this study. Even after normalizing the data by subject body mass, the female group showed significantly lower stiffness than the male group in 12 out of the 15 arm postures. The results highlight that 3D arm postures and sex significantly affect shoulder stiffness even under relaxed muscles. This study provides valuable foundations for future studies aimed at characterizing shoulder stiffness in the context of active muscles and dynamic movement tasks, evaluating changes in shoulder stiffness following neuromuscular injuries, and formulating rehabilitative training protocols for individuals suffering from shoulder problems.**

***Index Terms*— Shoulder joint mechanics, Shoulder mechanical impedance, shoulder stiffness**

I. Introduction

THE shoulder joint is one of the most intricate structures in the human body. As the basis of arm motion, adequate and stable control of the shoulder joint allows for the effective and natural control of distal joints (elbow and wrist) and sophisticated hand function during activities of daily living [1]. The stability of the shoulder joint is achieved through a complex interplay of bones, ligaments, tendons, and muscles, collectively providing resistance against external disturbances, often described as stiffness [2], [3].

Recent studies have also highlighted that females experience a higher incidence of shoulder injuries in occupational settings [4], [5] and during sports activities [6]. Another study has identified sex-specific differences in outcomes following anterior shoulder surgical stabilization [7]. Together, these findings suggest the potential for differences in shoulder joint stiffness between sexes in various contexts. Furthermore, despite extensive research into sex differences in the stiffness of other human joints, including the ankle [8], [9], knee [10], and elbow [11], and their underlying mechanisms, the exploration of sex differences in shoulder joint stiffness remains unaddressed. Our research aims to fill this knowledge gap by investigating the sex differences in shoulder joint stiffness, thereby enhancing our understanding of its role in sex-dependent shoulder joint stability and the risk related to shoulder injuries.

The system identification technique is a widely used method for characterizing joint stiffness. It estimates the relationship between the input joint angular position and the corresponding output joint torque. Previous research has primarily focused on characterizing shoulder joint stiffness within a two-dimensional (2D) horizontal plane. This was typically achieved using a planar robotic system that applied small position perturbations to a participant's hand [12]. This approach first characterized human end-point stiffness and subsequently decomposed it into elbow and shoulder joint stiffness components using a Jacobian matrix. The characterization was conducted under various conditions, including different tasks [12], [13], arm postures [14], and muscle contractions [15]. However, this approach is inadequate to isolate the shoulder joint stiffness for a specific degree-of-freedom (DOF). In contrast to the end-point stiffness approach, a different study applied perturbations directly to the shoulder joint. This was achieved using a single-DOF servo motor to characterize the shoulder joint stiffness in a 2D horizontal plane [16]. While these studies have significantly advanced our knowledge of shoulder joint stiffness modulation, their primary focus on the 2D horizontal plane limits a comprehensive investigation into

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stiffness characteristics in 3D space.

Recent research has aimed to address this limitation by characterizing the shoulder joint stiffness in 3D space. One study used a setup that integrated a 1-DOF servo motor and a crank arm to apply small position perturbations directly to the participant's shoulder joint in 3D space. This approach allowed for the characterization of shoulder joint stiffness across various arm postures [17] and under different volitional muscle contractions [18]. In another study, an exoskeleton robot attached to the forearm was utilized to apply position perturbations on the shoulder joint, specifically targeting internal/external rotation and horizontal abduction/adduction movements, and measure the corresponding torques in those specific directions. [19]. These recent studies provided significant insights into how shoulder joint stiffness is modulated under different conditions in 3D space, paving the way for a more refined understanding of human shoulder joint stiffness. However, the use of a single-DOF actuation systems presents several challenges. Maintaining consistent arm postures across different participants in 3D space is problematic due to the kinematic constraints of a single-DOF actuator. Additionally, each change in arm posture requires adjustments to the robot's setup, which considerably increases the duration of the experiments. Consequently, these prior studies have characterized shoulder joint stiffness in a relatively limited number of arm postures.

This study has two objectives. The primary objective of this study is to examine the relationship between various arm postures in 3D space and shoulder joint stiffness, particularly focusing on muscles in a relaxed state. The secondary objective is to investigate potential sex differences in the shoulder joint stiffness, which will advance our understanding of sex-dependent shoulder mechanics. To achieve these objectives, we utilized a custom-designed shoulder exoskeleton robot. This robot features a 4-bar spherical parallel manipulator (4B-SPM), enabling natural and unconstrained 3D arm motion [20].

Based on prior research that has demonstrated posture-dependent stiffness characteristics in various human joints [21]–[25], we hypothesize that shoulder joint stiffness is significantly influenced by arm postures in 3D space [17]. Additionally, in accordance with previous studies highlighting sex differences in the stiffness of other joints [8]–[10], we further hypothesize that shoulder joint stiffness in females is significantly lower than in males, even after accounting for variations in subject body mass.

II. Method

A. Participants

This study involved 40 healthy participants: 20 males (age: 24.8 (2.6) years, height: 171.1 (11.5) cm, mass: 67.5 (8.1) kg) and 20 females (age: 23.8 (4.1) years, height: 163.8 (8.5) cm, mass: 58.9 (7.3) kg). All participants were right-handed and had no history of neuromuscular disorders or shoulder injuries. The Arizona State University Institutional Review Board approved this study (STUDY 00009059), and written informed consent was obtained from each participant before data collection.

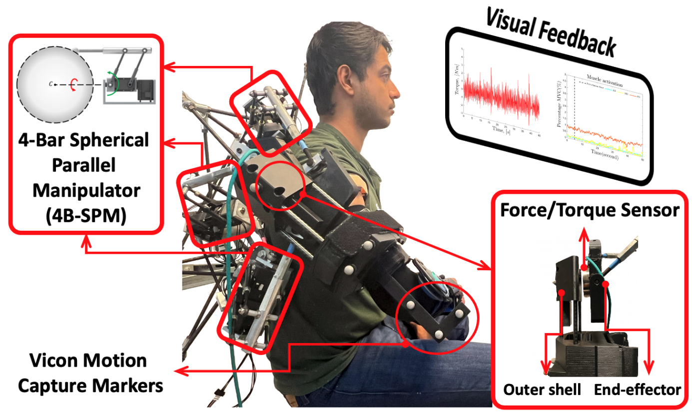

Fig. 1: Experimental setup for the characterization of shoulder joint stiffness. The 4B-SPM of the shoulder exoskeleton robot perturbs the participant's shoulder joint. Motion capture markers and a 6-axis force/torque sensor were utilized to measure shoulder kinematic and kinetic data, respectively. A visual feedback display provided real-time muscle activity of AD, MD, and PD shoulder muscles.

B. Experiment Setup

This study utilized the 4B-SPM shoulder exoskeleton robot, designed for generating three-dimensional rotational movements at the shoulder joint. The exoskeleton robot enables the positioning of a participant's arm in a range of postures within a 3D space. It consists of three substructures, each equipped with a pair of servo motors (Dynamixel MX-106R, Robotis, South Korea). These substructures work synergistically to control the orientation of the shoulder exoskeleton's end-effector plate, thereby modulating the angular position of the human shoulder joint. Since the 4B-SPM parallel mechanism places the actuators away from the end-effector plate, the robot can apply rapid and accurate perturbations directly to the participant's shoulder joint [20].

To accommodate various arm lengths and circumferences, two approaches were adopted. First, an appropriate arm interface module from two options with different radii, based on the subject's arm circumference, was selected. Additionally, a compressive strap was utilized to reduce the movement between the subject's arm and the robot. Secondly, the position and height of the chair were adjusted for each subject before the experiment to ensure that the center of rotation of the subject's shoulder aligned with that of the robot. Once aligned, the participant was instructed to freely move the arm over the entire 3D workspace. Any necessary adjustments were made to guarantee natural arm motion and to prevent any discomfort for the participant. Furthermore, to minimize the impact of varying elbow postures on shoulder stiffness characterization, an arm brace was used to maintain the elbow flexion angle at 90°. The reliability of this exoskeleton setup for characterizing shoulder joint impedance was validated in our previous study [26].

While the angular position of the exoskeleton, as determined by its Euler angles, can be measured via its built-in encoder feedback, previous studies have indicated that the encoder feedback from this particular prototype has an error margin of up to 1°, which is attributed to fabrication tolerances [27]. To enhance the accuracy of quantitative analysis of shoulder mechanics, a 3D motion capture system (Bonita 10 System by Vicon, UK) was used. This system tracks the movements of both the robot and human participants, ensuring highly precise position data. The position data in 3D space were captured using the Vicon Nexus2 (Vicon, UK), and the rotm2eul function in MATLAB Robotic System Toolbox (Mathworks Inc, Natick, MA) was used to transform these markers' positions into Euler angles.

Concurrently, shoulder torque was measured using a 6-axis force/torque (F/T) sensor (Axia 80 EDU by ATI-AI, NC, USA) that was mounted on the end-effector plate of the shoulder exoskeleton. On the opposite side of this plate, a set of parallel carbon fiber rods was connected to the outer shell of an upper arm cuff. This arrangement guaranteed a secure coupling of the exoskeleton to the human participant, aligning the sensor's center with the rotational center marked on the end-effector, which was crucial for the accurate measurement of the shoulder joint torque.

The measurement coordinate system was based on ZYX Euler angles, wherein the first, second, and third Euler angles represent shoulder flexion/extension, horizontal flexion/extension, and internal/external rotation of arm motion, respectively [28]. This convention aligns with the glenohumeral joint rotation axis as defined by the International Society of Biomechanics (ISB) [29], with our first, second, and third Euler angles corresponding to rotations about the Z, Y, and X axes of the glenohumeral joint, respectively.

All the motors operated under real-time position control using a PC (11th Gen Intel Core i7-11700 processor, 2.5 GHz) with the Robot Operating System (ROS, Melodic), and the system sampled all sensor data at a frequency of 250 Hz. To ensure that participants maintained a relaxed state of their shoulder muscles during the experiments, muscle activity of shoulder muscles was monitored using wireless surface electromyography (EMG) sensors (Delsys Trigno, MA, USA). These sensors were attached to the belly of three primary shoulder muscles: Anterior Deltoid (AD), Medial Deltoid (MD), and Posterior Deltoid (PD).

C. Experiment Protocols

The primary objective of this study is to characterize shoulder stiffness in a relaxed muscle state. Prior to the main experiment, maximum voluntary contraction (MVC) of the three primary shoulder muscles (i.e., AD, MD, and PD) was determined. During the main experiment, participants were instructed to relax their shoulder muscles, specifically not exceeding 5%MVC. To assist participants in maintaining the relaxed state, they were provided with real-time visual feedback on an LCD monitor, displaying the muscle activation (%MVC) for each of the three muscles.

The main experiment was designed to characterize the shoulder joint stiffness across 15 arm postures. These 15 arm postures are encompassed by the following 4 boundary configurations for the upper arm: 0° and 90° shoulder horizontal extension and 45° and 90° shoulder flexion. This range encompasses the most functionally relevant zone, covering a multitude of daily activities such as eating with a spoon, using a telephone, and reaching forward to receive an object [30], [31], as well as numerous occupational tasks and sports-related movements [32].

Upon positioning the participant's arm in each of the specified 15 postures in a randomized order, the robot directly applied small filtered Gaussian noise position perturbations (RMS: 2°, cutoff frequency: 3 Hz) to the shoulder joint in the horizontal flexion/extension direction for 45 seconds per trial. The perturbation amplitude chosen for this study was comparable to that used in previous joint impedance estimation studies [16], [33]. Two trials were performed at each arm posture, resulting in a total of 30 trials for the entire session. During trials, the robot supported the subjects' arm, and the steady-state torque due to arm weight was removed before applying the perturbations.

To avoid any potential effect of muscle fatigue on the characterization of shoulder stiffness, participants were given a break of at least 10 minutes after every 5 posture trials. Including the setup and breaks, the entire experiment was concluded in approximately two and a half hours.

D. Data Analysis

Shoulder stiffness was quantified by analyzing the relationship between input position perturbations and the corresponding output torque responses. Prior to establishing the input-output relationship, position, torque, and EMG data were processed. First, to minimize the effect of unintentional upper body movements, both the kinematic and torque data were high-pass filtered using a 2^{nd} order Butterworth filter with a cut-off frequency of 0.25 Hz [34]. The data was then decimated to 125 Hz. The EMG data was first demeaned and rectified, then filtered using a 500 ms moving average window, and normalized based on MVC.

The impulse response function (IRF) was estimated to describe the relationship between the shoulder joint's input position perturbations x and output torque measurements y,

$$\phi_{xy}(t,k) = \Delta t \sum_{j=M_1}^{M_2} \phi_{xx}(t-j,k-j)h(t,j) \tag{1}$$

where ϕ_{xy} is cross-correlation of input x and output y and ϕ_{xx} is auto-correlation of input x. The index j is the lag of the IRF, Δt is the sampling increment, and $M1$ and $M2$ are the minimum and maximum lags, respectively. The short data segment system identification method was employed to estimate the IRF h. This method integrates both time-invariant and time-varying correlation functions to estimate system dynamics over multiple short data segments [35]. Auto-correlation (ϕ_{xx}) and cross-correlation (ϕ_{xy}) function in this method are defined as:

$$\phi_{xx}(t,k) = \frac{1}{NR} \sum_{r=1}^{R} \sum_{i=t-N/2}^{t+N/2} x(i-k,r)x(i,r) \tag{2}$$

$$\phi_{xy}(t,k) = \frac{1}{NR} \sum_{r=1}^{R} \sum_{i=t-N/2}^{t+N/2} x(i-k,r)y(i,r) \tag{3}$$

where t is the middle time of each short data segment, i is a time point during the stationary period, N is the number of data points in the stationary period, r is the realization number, and R is the total number of realizations. The IRF is derived by integrating Eqs. (2) and (3) into Eq. (1) and then solving for the variable h. The shoulder joint stiffness is then estimated by integrating the IRF in the time window, defined by the minimum and maximum lags, at each sampling step Δt [36].

The quality of shoulder joint stiffness estimation was evaluated by quantifying the variance accounted for (%VAF) between the measured torque output y and the estimated torque $\hat{y}$, derived from the estimated IRF,

$$\%VAF = 100 \times \left(1 - \frac{var\,(y(t) - \hat{y}(t))}{var\,(y(t))}\right) \tag{4}$$

To compensate for any effect of the robot dynamics on the characterization, the robot's inherent stiffness without a human participant was quantified and then subtracted from the estimated shoulder joint stiffness for each of the 15 postures.

E. Statistical Analysis

We hypothesized that arm posture in a 3D space has a significant effect on shoulder joint stiffness, especially in the flexion/extension (FE) and horizontal flexion/extension (HFE) directions. A two-way repeated measures analysis of variance (ANOVA) was employed, with the two main factors of FE angle (three levels of angles between 45° and 90°) and HFE angle (five levels of angles between 0° and 90°). This allowed us to investigate the significant effects of the two main factors on shoulder joint stiffness and their interaction.

To further investigate variations in shoulder joint stiffness across different FE angles, we compared the stiffness values across three distinct FE angles. The representative stiffness for each FE angle was calculated by averaging the shoulder joint stiffness values from the five different HFE angles specific to that FE angle. Additionally, to investigate variations in shoulder joint stiffness related to changes in HFE angles, stiffness values at the end and middle of the range of motion (ROM) of HFE angles were compared for each of the three FE angles. For each FE angle, the stiffness at the end of ROM was determined by selecting the stiffness values at both ends of HFE postures (i.e., near 0° and 90° of horizontal extension). On the other hand, the stiffness in the middle of ROM was determined by selecting the stiffness value from the middle posture, corresponding to either 45° or 50° of horizontal extension among the five postures evaluated in this study.

We also hypothesized that sex differences exist in shoulder joint stiffness, particularly with females exhibiting lower stiffness compared to males. To test this hypothesis, a mixed ANOVA was employed, with sex as the between-subjects factor and arm posture as the within-subjects factor. To further investigate whether the sex difference in shoulder joint stiffness is attributed to size differences between males and females, an additional analysis was performed with body mass-normalized stiffness data. After conducting the mixed ANOVA, a *post-hoc* analysis was performed using an unpaired t-test for each of the 15 arm postures.

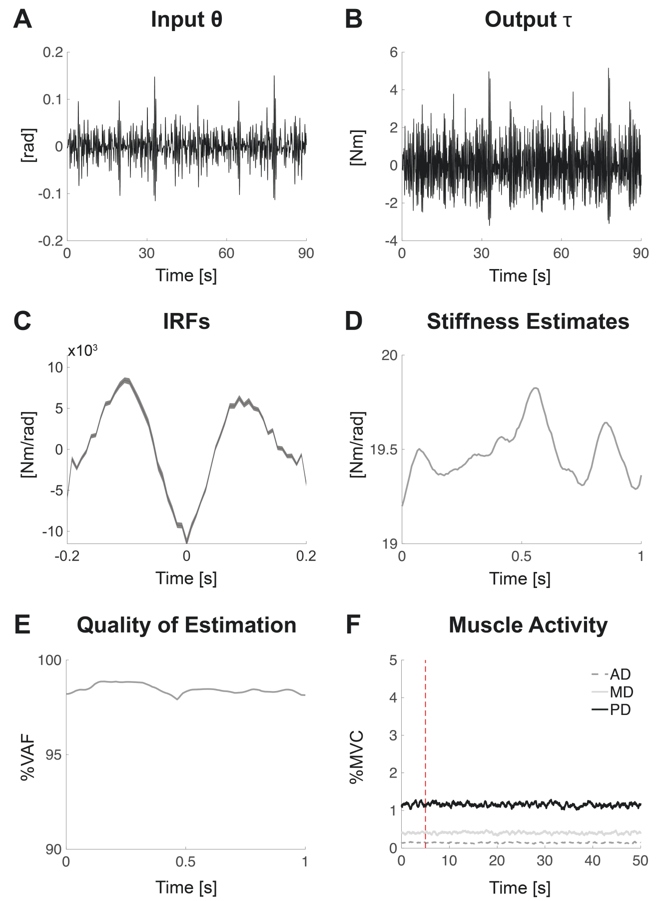

Fig. 2: Sample data and results of a representative participant at shoulder flexion of 67° and horizontal extension of 80°. (A) Input position perturbation in the HFE direction using a low-pass filtered Gaussian random signal with an RMS of 2° and a cutoff frequency of 3 Hz. (B) Torque output in response to position perturbation. Both input and output span 90 seconds, representing two trials. (C) Impulse response functions estimated at every one-second window with a lag size of 0.2 s in both directions. (D) Shoulder joint stiffness estimated over a one-second window by integrating IRFs. (E) Quality of shoulder joint stiffness estimation. (F) Muscle activity for AD, MD, and PD (red dotted line: perturbation initiation).

All statistical analyses were performed using SPSS (v28, IBM, USA) at a significance level of 0.05. Asterisks (***: $p < 0.001$, **: $p < 0.01$, *: $p < 0.05$) and error bars were presented in the result figures to denote statistical significance and mean ± standard deviation (SD).

III. Results

A. Sample Results of a Representative Participant

Sample results of a representative participant at shoulder flexion of 67.5° and horizontal extensions of 80° are presented in Fig. 2. Specifically, input position perturbations and the resulting output shoulder torques are shown in Fig. 2A and

TABLE I: Group average results of shoulder joint stiffness, quality of estimation, and muscle activity across all 15 postures

Flexion (°)	Horizontal Extension (°)	Shoulder joint stiffness (Nm/rad)	%VAF (%)	Muscle activity (%MVC) [AD,MD,PD]
45	20	18.3 (8.3)	95.5 (1.3)	0.9 (0.8), 0.6 (0.7), 0.5 (0.5)
	35	17.5 (6.4)	95.8 (1.2)	0.8 (1.0), 0.5 (0.7), 0.4 (0.3)
	50	13.1 (6.9)	96.4 (1.0)	0.7 (0.7), 0.4 (0.4), 0.4 (0.4)
	65	15.9 (6.6)	96.0 (1.4)	0.8 (1.0), 0.5 (0.6), 0.4 (0.4)
	80	22.1 (8.4)	95.9 (1.1)	1.0 (1.0), 0.5 (0.6), 0.4 (0.3)
67.5	10	13.6 (5.6)	96.7 (0.7)	0.8 (0.9), 0.9 (0.8), 0.5 (0.4)
	25	12.0 (6.1)	96.7 (0.8)	0.9 (1.0), 0.7 (0.6), 0.5 (0.4)
	45	12.1 (5.9)	97.1 (0.5)	1.0 (1.1), 0.6 (0.5), 0.5 (0.3)
	65	10.7 (4.8)	97.0 (0.7)	1.1 (1.2), 0.6 (0.6), 0.5 (0.4)
	80	15.2 (6.5)	96.9 (0.6)	1.1 (1.0), 0.4 (0.5), 0.5 (0.4)
90	0	11.1 (6.6)	97.0 (1.0)	0.7 (1.1), 0.7 (1.1), 0.6 (0.4)
	20	9.8 (7.0)	97.0 (0.9)	0.6 (0.9), 0.6 (1.0), 0.6 (0.4)
	45	8.6 (5.8)	96.9 (0.9)	0.6 (0.9), 0.5 (0.8), 0.7 (0.4)
	70	8.7 (4.7)	96.5 (1.0)	0.6 (1.2), 0.4 (0.5), 0.5 (0.4)
	90	13.3 (7.6)	96.6 (0.8)	0.8 (1.4), 0.5 (0.6), 0.5 (0.4)

The mean and standard deviation (SD) of all participants are presented.

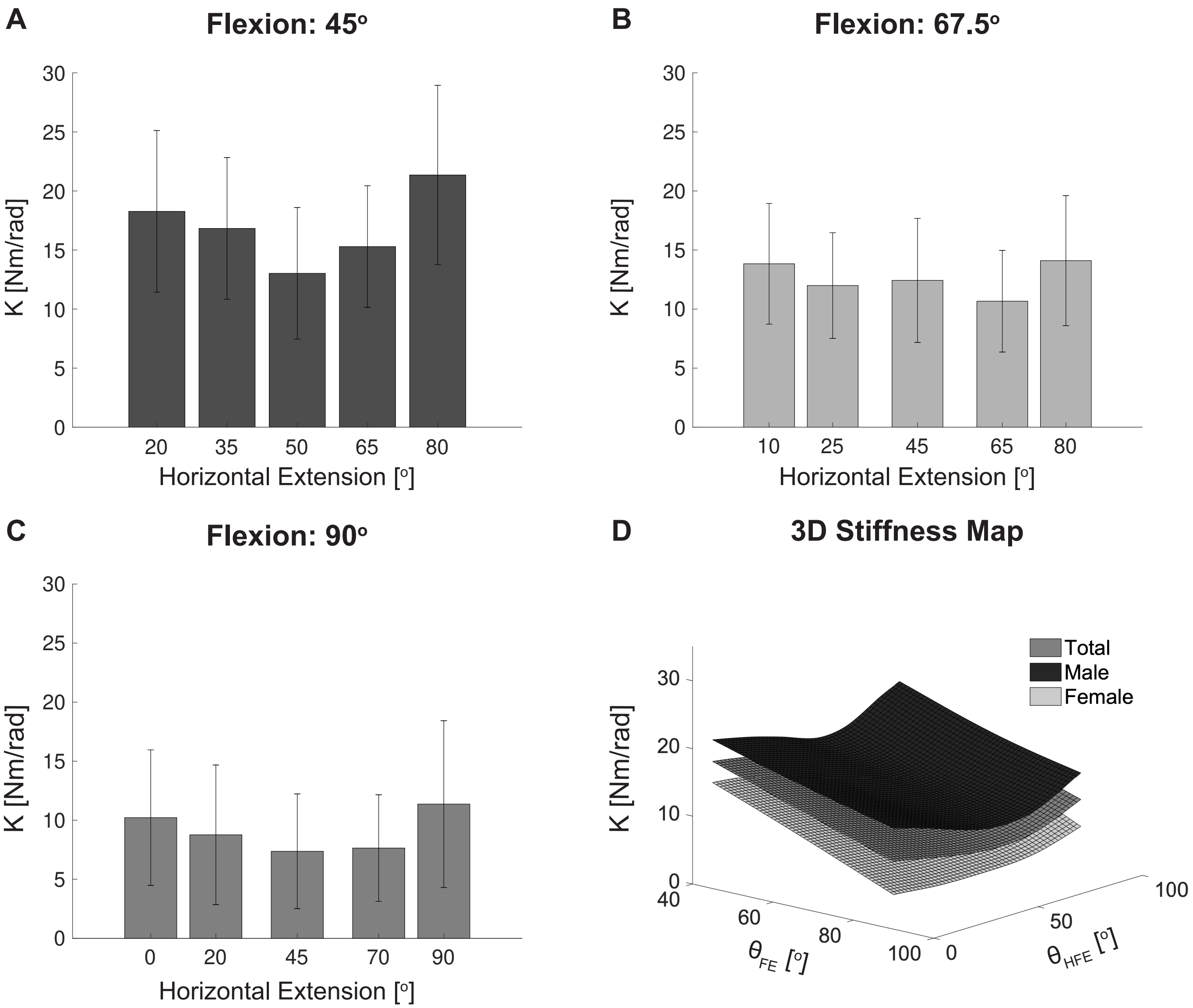

Fig. 3: Group average results of shoulder joint stiffness at 15 arm postures. (A-C) Shoulder joint stiffness at 45°, 67.5°, and 90° flexion, respectively. (D) Arm posture-dependent shoulder joint stiffness (θ_{FE}: Flexion-extension angle and θ_{HFE}: Horizontal flexion-extension, Black: All participants, Dark gray: Male participants, Light gray: Female participants).

2B, respectively. For the purpose of short data segment system identification, the position and torque data were divided into 90 one-second segments.

The IRFs were estimated at every time step within the one-second window using Eqs. (1) - (3), with a lag size of 0.2 seconds in both positive and negative directions (Fig. 2C). From each IRF estimate, stiffness was estimated by simply integrating the IRF. The single representative shoulder joint stiffness (K) for this specific posture was subsequently determined by averaging all the stiffness estimates within the one-second window (Fig. 2D). The results of %VAF corresponding to the stiffness estimation are presented in Fig. 2E. The average shoulder stiffness (K) and %VAF for this sample trial are 19.5 Nm/rad and 98.5%, respectively. EMG data from this sample trial showed that the participant maintained muscle activation below 5% MVC, suggesting a relaxed muscle state during stiffness characterization (Fig. 2F).

The group average results of shoulder joint stiffness, quality of system identification (%VAF), and muscle activity (%MVC) across all 15 arm postures and for all 40 participants are summarized in Table I. The quality of system identification was notably high, with an average %VAF of 96.5 (0.5)%. The group average results of muscle activity also showed that participants consistently maintained relaxed muscles, with average muscle activation of 0.8 (0.2)%, 0.6 (0.1)%, and 0.5 (0.1)% for AD, MD, and PD, respectively. For clarity, all subsequent group results are presented as mean (SD) without further explanation.

B. Effect of Arm Postures on Shoulder Joint Stiffness

The results from the two-way repeated measures ANOVA revealed a significant impact of arm postures on shoulder joint stiffness (Fig. 3). This was evident from the significant main effects of FE angle ($F_{2,78} = 37.5$ $p < 0.001$) and HFE angle ($F_{4,156} = 37.0$, $p < 0.001$). Additionally, a significant interaction was observed between these two within-subject factors ($F_{8,312} = 4.2$, $p < 0.001$), which was primarily due to the fact that the patterns of stiffness change across HFE angles are not consistent at different FE angles.

Shoulder joint stiffness increased consistently with a decrease in the shoulder flexion angle. The stiffness values were 17.4 (3.3), 12.7 (1.7), and 10.3 (1.9) Nm/rad for shoulder flexion of 45°, 67.5°, and 90°, respectively (Fig. 4A). Specifically, the stiffness at flexion angles of 45° and 67.5° was 68.6% ($p < 0.001$) and 23.6% ($p < 0.009$) greater than that at flexion angle of 90°, respectively.

Additionally, shoulder stiffness showed a clear increasing pattern as the arm configuration approached either end of the shoulder ROM in HFE, specifically near 0° or 90° horizontal extension. Comparative analysis revealed that stiffness increased by 54.4%, 18.7%, and 41.1% at the end of ROM compared to the middle of ROM for flexion angles of 45°, 67.5°, and 90°, respectively. Out of the six pairs analyzed, five exhibited statistical significance ($p < 0.01$). Although one remaining pair, consisting of 10° and 45° horizontal extension at the 67.5° flexion angle, did not reach the statistical significance ($p = 0.48$), it still followed the same trend, with stiffness values at both ends of the ROM being greater than that in the middle of ROM (Fig. 4B).

C. Sex Differences in Shoulder Joint Stiffness

The results of the mixed ANOVA demonstrated that sex significantly affected shoulder joint stiffness, with male stiffness being higher than female stiffness ($F_{1,38} = 43.7$, $p < 0.001$). Additionally, a significant interaction effect was observed between arm postures and sexes ($F_{14,532} = 2.1$, $p = 0.013$), which was primarily because the pattern of stiffness change across HFE angles was less pronounced in females than in males, particularly at higher flexion angles. Subsequent *post-hoc* analysis results from unpaired t-tests revealed that sex

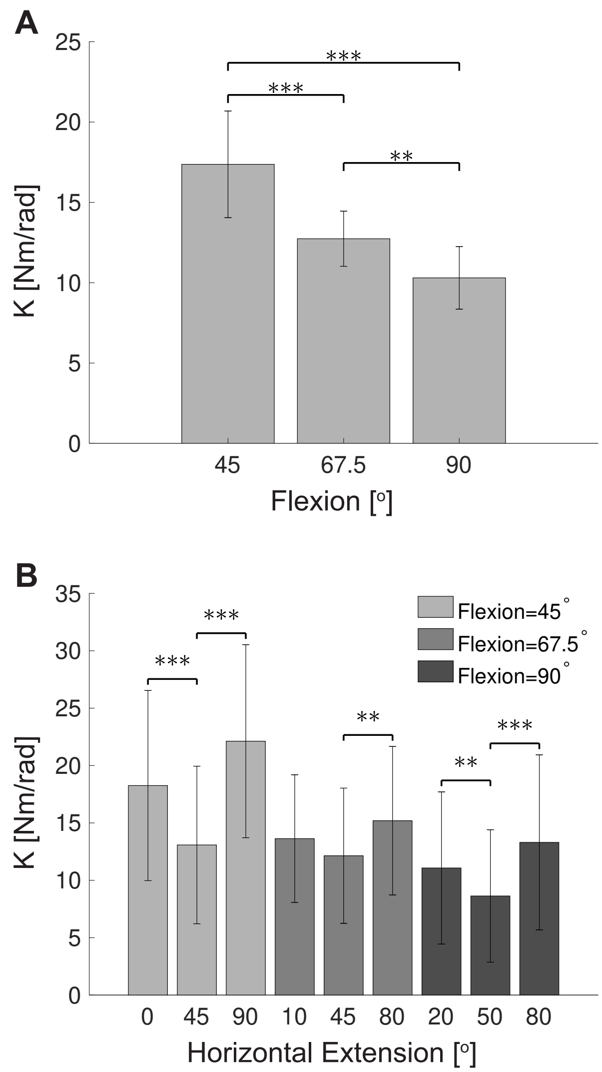

Fig. 4: (A) Comparison of shoulder stiffness at three distinct flexion angles. The representative stiffness at each flexion angle was computed by averaging the stiffness values across 5 HFE angles. Stiffness decreased as the flexion angle increased from 45° to 90°. (B) Comparison of shoulder stiffness in the middle versus the end of ROM in HFE. For all three flexion angles examined, shoulder stiffness at the end of ROM was consistently higher than in the middle of ROM.

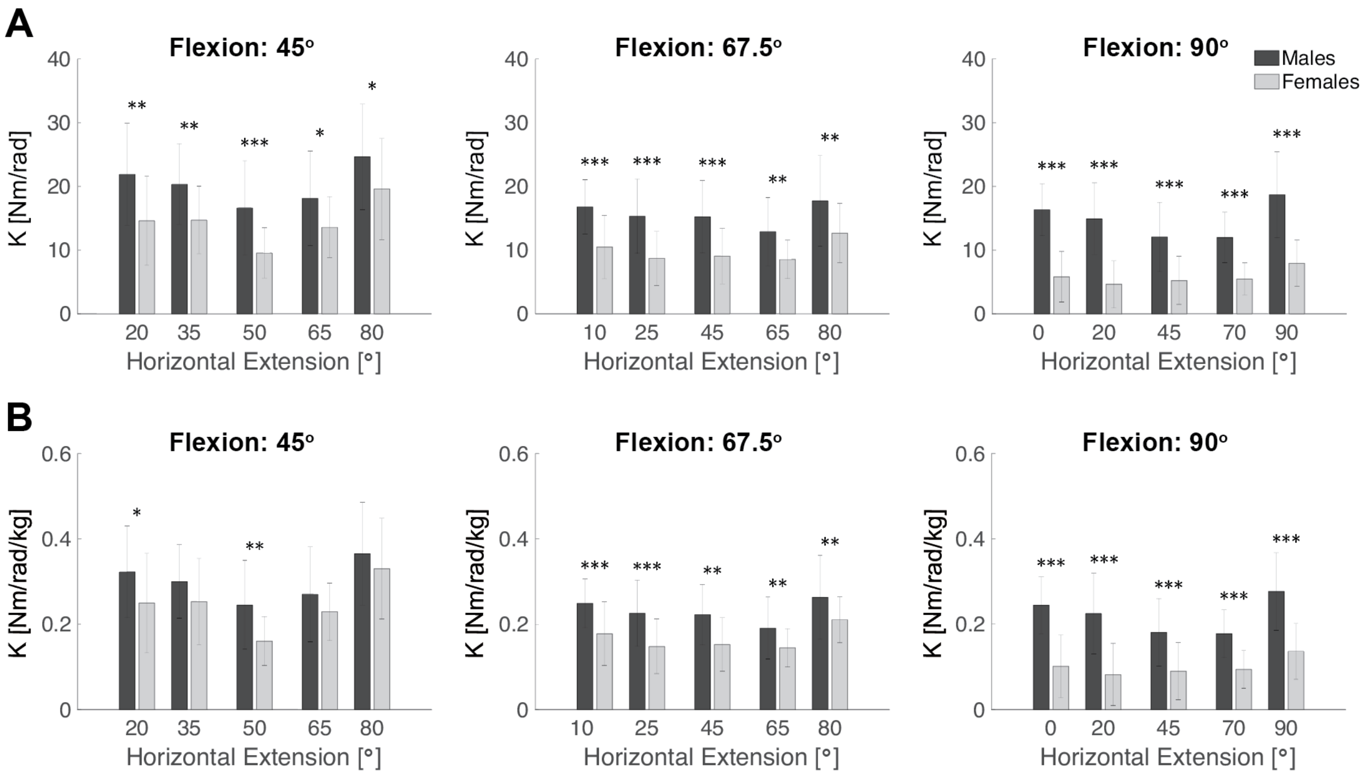

Fig. 5: Comparison of shoulder joint stiffness between males (dark gray) and females (light gray) across 15 arm positions. (A) Comparison results with original data sets. Statistical difference was observed in all 15 arm postures. (B) Comparison results with body mass-normalized data sets. Statistical difference was observed in 12 out of 15 arm postures. For the remaining 3 postures, male stiffness still remained higher than female stiffness.

had a significant impact on shoulder joint stiffness in all 15 postures (Fig. 5A).

The body mass-normalized shoulder joint stiffness data also showed a significant sex effect ($F_{1,38} = 33.0$, $p < 0.001$) and interaction effect between arm postures and sexes ($F_{14,532} = 2.6$, $p = 0.001$). The unpaired t-tests showed that sex had a significant impact on shoulder joint stiffness in 12 out of the 15 postures. Although statistical significance was not reached for the remaining 3 postures, they still exhibited the same trend of male stiffness being greater than female stiffness (Fig. 5B).

IV. Discussion

This study demonstrates that shoulder joint stiffness varies across different arm postures, even without significant muscle activation (below 5%MVC), suggesting that such variations are primarily attributed to the intrinsic mechanics of the shoulder joint rather than compensation through neural control or muscle reflexes. Notably, stiffness increased as the shoulder flexion angle decreased, as well as when the arm approaches the limits of the shoulder ROM. Moreover, the study revealed sex differences in shoulder joint stiffness across different arm postures, which are not simply the result of body mass differences between males and females.

Similar to observations in other human joints, such as the ankle [25], [37] and wrist [22], our study found that shoulder joint stiffness exhibits significant variation depending on the joint position. Our findings are consistent with previous research, showing an increase in shoulder stiffness as arm elevation (flexion) decreases and as the shoulder approaches the limits of its ROM in HFE directions. Notably, the lowest shoulder joint stiffness observed in one previous study was 9.1 Nm/rad at an arm posture of 90° flexion and 60° horizontal extension [17], which aligns with our result of 8.7 Nm/rad at an arm posture of 90° flexion and 70° horizontal extension.

Previous anatomical studies on the shoulder joint may offer insights into the observed variation in shoulder joint stiffness across different arm postures. Specifically, several studies utilizing magnetic resonance imaging and X-ray imaging have demonstrated that elevating the arm posture in the shoulder flexion direction induces a shift in the relative position of the humeral head with respect to the glenoid [38], [39], which could potentially diminish their contact. Such a reduction in contact decreases the compression force in the joint [40] and may decrease the shoulder joint stiffness accordingly.

In addition, several studies have identified alterations in the strain of key ligaments of the shoulder joint, such as the glenohumeral ligament [41], [42] and coracohumeral ligament [43] as the shoulder HFE angle changes. These ligaments show some laxity in the middle of ROM, but become tightened as the shoulder reaches the limits of its ROM. Moreover, one study has demonstrated the similar behavior of the biceps tendon when approaching the limits of shoulder ROM [44]. This tensioning likely contributes to the increased shoulder stiffness observed around the limits of ROM in HFE.

Our study demonstrates significant sex differences in shoulder joint stiffness, with females consistently exhibiting lower stiffness compared to males in both original and body mass-normalized stiffness. These results are consistent with previous studies that have identified significant sex differences in the stiffness of other joints, such as the ankle and knee joints [9], [10]. The lower shoulder joint stiffness in females may be attributed to anatomical factors, such as increased laxity and flexibility [45], [46] and a smaller and thin glenoid [47] when compared to males. This result is important because lower shoulder joint stiffness in females may explain the higher incidence of shoulder injuries observed in females due to decreased joint stability [48], [49].

The current study has several major limitations. Firstly, perturbations were applied only in the direction of horizontal flexion and extension because applying perturbations in various directions would significantly increase the duration of the experiments, leading to concerns about the potential for compromised data quality due to participant fatigue. Our current protocol, which focuses on a single direction of perturbation across 15 different arm postures, requires approximately two and a half hours per participant. Future research could explore multiple directions of perturbation, using methodologies designed to mitigate the effects of extended experiment durations and participant fatigue, thus providing a more comprehensive understanding of shoulder joint stiffness. Secondly, the scope of this study was confined to characterizing shoulder joint stiffness in a state of relaxed muscles, thereby solely examining the contribution of passive mechanics - such as ligaments, tendon, and passive muscles - to shoulder joint stiffness. Thirdly, the characterization was conducted during static arm postures. Future studies seem warranted to investigate the modulation of shoulder joint stiffness during various conditions of muscle activation and dynamic arm movements. Another future direction would involve investigating altered shoulder joint stiffness due to neurological impairments (e.g., stroke). The results of the current study will provide a baseline for understanding changes in shoulder mechanics in such conditions.

In conclusion, the current study investigated the effects of varying arm postures in 3D space on shoulder joint stiffness, with consideration of sex differences. The outcomes of this study, along with those from future studies aimed at characterizing shoulder joint stiffness under various task conditions (e.g., dynamic shoulder movement, muscle co-contraction), would provide valuable insights that can be applied in various domains, including physical therapy, rehabilitation robotics, and assistive robotics.

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