Abstract—Arm impairments in patients post stroke involve the shoulder, elbow and wrist simultaneously. Patients may develop spasticity and reduced range of motion (ROM) at the multiple joints with abnormal couplings between the multiple joints and between the multiple degrees of freedom (DOF). They may lose independent control of individual joints and coordination among the joints. This project is aimed at developing a whole arm intelligent rehabilitation robot capable of controlling the shoulder, elbow, and wrist individually and simultaneously while allowing trunk motions, with the following integrated features: 1) it has unique diagnostic capabilities to determine which joints and which DOFs have significant changes in the neuromechanical properties, which joints lose independent control, what are the abnormal couplings, and whether the problem is due to changes in passive muscle properties or active control capabilities; 2) based on the diagnosis, it stretches the spastic / deformed joints forcefully under intelligent control to loosen up the specific stiff joints/DOFs; 3) with the stiff joints loosened up, the patients practice voluntary functional movements with assistance from the robot to regain/improve their motor control capability; and 4) the outcome is evaluated quantitatively at the levels of individual joints, multiple joints/DOFs, and the whole arm.

I. INTRODUCTION

Spasticity, contracture, muscle weakness, and motor impairment are commonly seen following stroke. The several symptoms are closely related to each other and are major factors contributing to disabilities in patients post stroke [1-7]. The hypertonus and reflex hyperexcitability disrupt the remaining functional use of muscles, impede motion, and may cause painful muscle spasms. Loss of muscle control, weakening and fatiguing of muscles, lack of appropriate joint movement, prolonged spasticity and associated painful muscle spasms may be accompanied by structural changes of muscle fibers and connective tissue, which may result in a reduction in joint range of motion (ROM) and lead to a clinical contracture, joint deformity, and motor impairment [3, 7-13].

Several stereotypical patterns of arm deformity with multiple joints involved are commonly seen in patients with neurological impairments, including adducted/externally rotated shoulder, flexed elbow, pronated forearm, flexed wrist, and clenched fist [14]. There is a strong need to treat the deformed/hypertonic arms and multiple involved joints simultaneously on a frequent basis to reduce spasticity/contracture and increase mobility, which is addressed in this study.

For most patients post stroke, physical therapy is the cornerstone of the rehabilitation process [15-18]. Physical therapy is important and effective in treating persons with hypertonic/deformed limbs [15, 16, 18, 19]. A physical therapist uses physical modalities, functional training, exercises, and one-on-one manual manipulation of the stroke patient’s body with the intent of reducing spasticity and contracture and restoring movement function. However, the effects may not be long lasting, partly due to the limited and sometime infrequent therapy a patient can receive. Practically, the manual stretching is laborious and the outcome is dependent on the experience and subjective “end feeling” of the therapists. For both the patients and therapists, there is a need for a device that can stretch and mobilize the joints precisely, reliably, and effectively [16, 18-20].

For effective treatment, it is very important to accurately diagnose the multi-joint and multi-DOF arm impairments. Motor impairments in patients post stroke affect the multiple joints of the arm simultaneously. In terms of joint biomechanical properties, patients may develop spastic hypertonia and reduced ROM at multiple joints with abnormal coupling among the joints and with multiple DOFs at each joint [14]. In terms of voluntary control, patients post stroke may lose independent movements of individual joints and coordination among the joints [21]. There is a strong need to diagnose the multi-joint/DOF pathological changes and then treat the shoulder, elbow and wrist joints in well coordinated ways. However, it is not practical for a clinician to evaluate the increased resistance and abnormal couplings at the multiple joints and multi-DOFs simultaneously and quantitatively. This study is aimed at performing such more accurate and comprehensive diagnosis/evaluation using a novel robotic device and use the information obtained to guide subsequent treatment/training.

A number of rehabilitation robotic devices have been used to exercise the involved joints and reduce joint spasticity/contractures. For example, the continuous passive motion (CPM) device is widely used in clinics and in patients’ home to move a joint within a pre-specified movement range, to prevent postoperative adhesion and reduce joint stiffness [22]. Advanced robot-aided devices have also been developed to evaluate arm impairment quantitatively, and to assist and guide patient’s hand to reach a target in the arm workspace to enhance neurorehabilitation following brain injury [23-26]. However, existing devices...
like the CPM machine move the limb at a constant speed between two preset joint positions. When it is set within the flexile part of the ROM, the passive movement does not usually stretch into the extreme positions where contracture/spasticity is significant. On the other hand, setting a CPM machine too aggressively may risk injuring the joint because the machine controls the joint position or velocity without incorporating the resistance torque generated by the soft tissues. There is a need for a device that can safely stretch the joint(s) to the extreme positions with accurate control of the resistance torque and stretching velocity. Furthermore, there is a need to follow up the strenuous passive stretching with training of active movement and to evaluate the impairment and rehabilitation outcome quantitatively and objectively.

The purposes of the study are to develop a new whole-arm intelligent rehabilitation robot (called IntelliArm) capable of controlling the shoulder, elbow, and wrist individually and simultaneously, which helps to achieve effective stroke rehabilitation. Based on the following features incorporated into the IntelliArm: 1) it has unique diagnostic capabilities for individual patients including information on which joints and which DOFs are impaired, what are the abnormal couplings, and whether the problem is due to passive muscle properties or active control capabilities; 2) based on the diagnosis, it stretches the hypertonic/deformed arm of the patients post stroke under intelligent control to loosen up the specific stiff joint(s) or to break up abnormal couplings between joints/DOFs so that the CNS can potentially control the relevant muscles and arm movement more effectively; 3) with the stiff joints loosened up, the patient performs voluntary reaching tasks to regain/improve their motor control capability; 4) the outcome is evaluated quantitatively at the levels of individual joints, multiple joints/DOFs, and the whole arm.

II. METHODS

A. To develop a novel IntelliArm and perform patient-specific diagnosis of the passive and active biomechanical changes at the shoulder, elbow, and wrist

In the passive mode, the multi-joint arm robot moves the shoulder, elbow, and wrist of the impaired arm of patients post stroke throughout the ROMs both simultaneously and individually under precise control with the multi-axis torques and positions measured at the shoulder, elbow, and wrist simultaneously. In the active mode, the patient is asked to move the impaired joints individually and the multiple joints of the whole arm simultaneously for functional movements such as reaching, with the multi-joint and multi-DOF dynamic properties measured at the shoulder, elbow, and wrist simultaneously. Multi-joint and multi-DOF analysis is done on the data from the passive and active movements to diagnose the multi-joint biomechanical changes in the impaired arm, which is directly useful in guiding rehabilitation of the impaired arm in the subsequent aims.

A.1 IntelliArm Designed to Diagnose Multi-Joint/Multi-DOF Biomechanical Changes

A custom-developed unique IntelliArm is used to diagnose the biomechanical changes and abnormal couplings at the shoulder, elbow, and wrist joints of the impaired arm of patients post stroke (e.g., which part of the passive or active workspace is deficient, which joints and which DOFs are stiff and which joints at what arm postures are coupled abnormally) (Fig. 1).

The shoulder, elbow and wrist is controlled in 7 active DOFs individually by 7 servomotors plus 2 passive DOFs, which is important in natural functional arm movements (Fig. 1). The robotic arm is mounted on an X-Y-Z table with the vertical Z-axis driven by a linear actuator and free to slide passively in the X-Y directions (Fig. 1). The glenohumeral joint is controlled actively in 3 DOFs: horizontal abduction/adduction, flexion/extension, and internal/external rotation. Considering arm elevation involves both glenohumeral and scapular elevations and thus the glenohumeral joint moves in the vertical plane, the linear actuator controlling in the vertical direction and the free sliding in the mediolateral direction helps keep the robotic arm aligned with the glenohumeral joint. Furthermore, considering stroke survivors often use trunk leaning to compensate for their reaching motion, the robotic arm is free to slide in the anteroposterior direction to avoid unnatural restraints (Fig. 1). At the elbow, patients post stroke often develop pronation deformity of the forearm, it is important to move and evaluate the forearm in a proper range of pronation. The forearm is mounted to a circular guide through a forearm brace and controlled by a servomotor through a cable-driven mechanism, which allows controlled movement of forearm supination-pronation. The wrist is driven in flexion/extension by the wrist motor. The multi-DOF active driving is controlled by a central digital controller.

![Fig. 1. The IntelliArm designed to diagnose, treat with both passive stretching and active functional movements, and evaluate multi-joint and multi-DOF biomechanical changes including the shoulder, elbow and wrist in the impaired arm of patients post stroke. The subject is seated with the arm, forearm and hand attached to the IntelliArm through corresponding braces (not shown in the figure for clarity). The shoulder platform can move in three orthogonal](image-url)
directions (free sliding in the anteroposterior (A-P) and mediolateral (M-L) directions, and driven actively in the vertical direction) relative to the base (not shown for clarity) along linear guides in the X-Y-Z directions, which allows the robotic arm aligned with the glenohumeral joint. The glenohumeral joint was driven in horizontal abduction/adduction, flexion/extension and arm rotation; the elbow and wrist are extended/flexed by the elbow and wrist motor, respectively. The forearm is supinated/pronated by the forearm twisting servomotor.

The 7-DOF robotic arm is based on a similar 4-DOF robotic arm, which has been developed and applied to stroke rehabilitation (Fig. 2).

Fig. 2. A 4-DOF robotic arm designed to treat the impaired arms of patients post stroke and evaluate multi-joint biomechanical changes including the shoulder, elbow and wrist. The subject is seated with the arm, forearm and hand attached to the IntelliArm through corresponding braces. The shoulder, elbow and wrist are extended/flexed by the shoulder, elbow and wrist motor, respectively. The forearm is supinated/pronated by the forearm twisting servomotor. The whole robotic arm is mounted on a large X-Y table, allowing the glenohumeral center of rotation to move in the A-P and M-L directions.

To diagnose arm impairment in terms of multi-joint biomechanical properties, it is important to move the arm throughout its range of motion. Direct driving of each joint/DOF at its axis using a servomotor provides large physiological ranges of motion at the shoulder, elbow, forearm and wrist (Figs. 1 and 2), which is important in the multi-joint and multi-DOF diagnosis.

Six-axis resistance torques/forces is measured at each of the joints including the shoulder, elbow and wrist (Figs. 1 and 2). Each of the 7 DOFs plus the 2 passive DOFs are measured by encoders built in the servomotors or potentiometers mounted on the X-Y-Z table. The comprehensive kinetic and kinematic measurements allow us to evaluate the increased stiffness, abnormal couplings among the multiple joints and multi-DOFs, and loss of individuation to diagnose the pathological changes difficult to do in a manual examination by a clinician.

A.2 Diagnosis of Biomechanical Changes in the Impaired Arm

The subject sits upright comfortably on a sturdy barber’s chair, with the trunk strapped to the backrest. The arm, forearm and hand are strapped to their corresponding braces, with the relevant axes of the IntelliArm aligned with the arm at the shoulder, elbow, and wrist (Figs. 1 & 2). The position of the elbow and wrist servomotors can be adjusted along the arm and forearm for different arm and forearm lengths.

In diagnosing the multi-joint and multi-DOF biomechanical changes, the IntelliArm operates in both passive and active modes. In the passive mode, the multi-joint robot moves the shoulder, elbow and wrist of the impaired arm of patients post stroke throughout the ROMs both simultaneously and individually in well-controlled patterns with the multi-axis torques and positions measured at the shoulder, elbow and wrist simultaneously. In the active mode, the patient moves the impaired arm voluntarily and the multi-joint and multi-DOF dynamic properties are measured at the shoulder, elbow and wrist simultaneously.

B. To stretch the shoulder, elbow and wrist joints of the impaired arm strenuously and safely under intelligent control based on the above diagnosis to reduce hypertonia and abnormal coupling at the joints involved

From the above, the joints (and DOFs) with excessive coupling and/or increased stiffness and the associated arm postures are identified, the IntelliArm stretches all the joints simultaneously in general between the curled arm positions in front of the body and positions with extended/abducted/externally rotated shoulder, extended and supinated elbow, and extended wrist. We also focus more on the joints/DOFs which need to be loosened up based on the above individual diagnosis. The IntelliArm is under novel multi-joint intelligent control to stretch the joints forcefully and safely in well-coordinately patterns. On the one hand, for safe treatment, the stretching velocities decreases with increasing resistance torques at the multiple joints involved and each joint is stretched according to its own condition and the conditions of the coupled joints. On the other hand, for effective treatment, the stretching does not stop until pre-specified peak resistance torques are reached at the joints involved (and at individual DOFs). The stretched arm is held at the extreme positions for a period of time to let stress relaxation occur before the joints are moved to other extreme positions.

B.1 Stretch Multiple Joints/Multi-DOFs under Intelligent Control

The shoulder, elbow and wrist of the impaired arm with deformity/hypertonia in patients post stroke are stretched forcefully and safely under intelligent control to loosen up the stiff muscles and joints (Fig. 1). The subject is seated upright comfortably on a barber chair, with the trunk strapped to the backrest. The arm, forearm and hand are strapped to the IntelliArm through an arm, forearm and hand braces, respectively. A clamp can be used to fix any of the braces to the robotic arm more securely.
In this project, we focus on the shoulder, elbow and wrist stretching while keep the hand position fixed. The hand including fingers are held in a hand brace, which keeps the hand in a relatively straightened position while the shoulder, elbow and wrist are being stretched dynamically. Of note is that although the fingers are just held statically by the brace, due to the coupling between the fingers and the other joints, the fingers may still be stretched dynamically during the motor-controlled stretching of the wrist and elbow joints.

B.2. Novel Control of the Intelligent Stretching at the Individual Joints

The IntelliArm is driven by 7 servomotors controlled by a digital controller, which can either drive all or several of the joints/DOFs simultaneously or drive a joint individually (Fig. 1). Based on the diagnosis, we know which joints are stiff, coupled abnormally, and need to be loosen up. For each servo system, the digital controller reads the joint position and resistive torques and adjusts the stretching velocity accordingly [27-29].

Based on a novel intelligent stretching strategy, the digital controller controls the stretching velocity at each joint according to the resistance torque as follows. Near the end of ROM, the increasing resistance slows down the motor gradually, which is critical for safe operation. Furthermore, the stretching does not stop until a pre-specified peak resistance torque is reached. In this way, the muscle-tendons involved are stretched strenuously and safely, which likely results in a larger ROM. Once the specified peak resistance torque is reached, the servomotor holds the joint at the extreme position for a period of time (e.g., 5 sec during each cycle of the back-and-forth stretching), as used by a therapist. In the middle ROM where the resistance is usually low, the motor stretches the slack muscles quickly at higher speeds. As a safety precaution, position limits can be set by the operator and they are monitored by the digital controller together with the torque limits. Specifically, the following rules are implemented in the digital controller to adjust the motor velocity \( V(t) \) every 0.5ms:

\[
\begin{align*}
V(t) &= \begin{cases} 
0, & \text{if } (M_{\text{p}}(t) \geq M_p) \text{ or } (\theta(t) \leq \theta_p + \theta_d) \text{ and need to hold} \\
\frac{C}{M_{\text{p}}(t)} V_{\text{max}}, & \text{if } (M_{\text{p}}(t) \geq M_p) \text{ and } \theta(t) \geq \theta_p + \theta_d \text{ and have held long enough} \\
\frac{C}{M_{\text{p}}(t)} V_{\text{max}}, & \text{if } 0 < M_{\text{p}}(t) < M_p \text{ and } \theta(t) \geq \theta_p + \theta_d \\
\frac{C}{M_{\text{p}}(t)} V_{\text{max}}, & \text{if } -M_p < M_{\text{p}}(t) < 0 \\
\frac{C}{M_{\text{p}}(t)} V_{\text{max}}, & \text{if } (M_{\text{p}}(t) \leq -M_p) \text{ and } \theta(t) \leq \theta_p - \theta_d \text{ and have held long enough} \\
\frac{C}{M_{\text{p}}(t)} V_{\text{max}}, & \text{if } (M_{\text{p}}(t) \leq -M_p) \text{ and } \theta(t) \leq \theta_p - \theta_d \text{ and need to hold} 
\end{cases}
\]

where \( \theta(t) \) and \( M_{\text{p}}(t) \) are the joint position and resistance torque at time \( t \), respectively. \( M_p \) and \( M_n \) are the specified peak resistance torque at the positive and negative ends of the joint ROM, respectively (both are positive numbers). \( V_{\text{max}} \) (positive numbers) are the magnitudes of the lowest (for stretching in the joint extreme positions) and highest speed (for stretching in the mid-ROM), respectively. \( C \) is a constant, scaling the \( 1/M_{\text{p}}(t) \) to the appropriate stretching velocity. \( \theta_p \) and \( \theta_d \) are the specified positive and negative end of the ROM, respectively. \( \theta_d \) (a non-negative number) represents the allowed further rotation beyond the position limits (to leave room for stretching-induced improvement in ROM). If \( \theta_p \) is chosen to be a very large number (to allow the device move beyond the position limits) or if \( \theta_p \) and \( \theta_d \) are set outside the ROM, the stretching control is dominated by the resistance torque (the stretching is still safe) and the motor reverses its rotation once the specific resistance torque is reached for the specified amount of time. On the other hand, if \( M_p \) and \( M_n \) are choose to be very large, the stretching is restricted by the position limits. In general, we want the stretching reaches the torque limits at both ends of the ROM with the position limits incorporated into the control scheme as a safety measure and as an optional mode of stretching, therefore the \( \theta_p \) and \( \theta_d \) are set to approximately match the ROM by manually pushing the joint to its extreme positions (or by entering their values through the keyboard) and the \( \theta_d \) is chosen as a positive number (e.g., 5\(^\circ\)). In this way, the torque limits are reached most of the time, while the position limits still restrict potential excessive joint movement. All the control parameters can be adjusted conveniently within pre-specified ranges.

The digital controller checks the joint position and torque signals 2000 times per second and will shutdown the system if they are out of pre-specified ranges. Mechanical and electrical stops can be used to restrict the motor range of motion. The operator and the patient each have a stop switch, and either of them can shut down the IntelliArm by pressing the switch.

B.3 Control of Multiple Joints Cooperatively

Considering that there are dozens of muscles and other soft tissues crossing the shoulder, elbow, and wrist joints and some crossing two joints, movement and control of the shoulder, elbow and wrist joints are closely coupled. Furthermore, the couplings may be increased considerably in hypertonic and deformed arms of patients post stroke, as seen in the pilot study. For more effective treatment of hypertonic arms, the shoulder, elbow and wrist should be treated together in a well-coordinated way. Considering the arm deformity is characterized with adducted and internally rotated shoulder, flexed elbow and wrist and pronated forearm, and hypertonia may exist in both extension and flexion ends of the joints, the shoulder, elbow, and wrist joints are stretched simultaneously by the IntelliArm between overall whole arm stretched out and curled in positions.

There are infinite number of possible control modes during the stretching between the whole arm curled position to the whole arm extended and stretched out position. In the 7-D joint space with 7-DOF active control at the shoulder, elbow and wrist, there are infinite number of paths between the whole arm curled position to the whole arm stretched position. The specific control mode or hand path is dependent on the ROMs and stretching speed at the shoulder, elbow, and wrist. The multiple joints and DOFs are stretched following the several rules:

Start with a neutral position with shoulder at 60\(^\circ\) abduction and 30\(^\circ\) flexion, elbow at 60\(^\circ\) flexion, wrist at 25\(^\circ\) flexion, and forearm at the 60\(^\circ\) supination. If the patient’s arm can not be put at the posture comfortably, the closest position is used.
Stretch the shoulder into abduction/extension/external rotation, elbow and wrist into extension, and forearm into supination simultaneously under intelligent control with specified peak resistance torques and stretching velocity decreased with increasing resistance, as described above for individual joints/DOFs (Eq. (1)).

When one joint or DOF reaches the extreme extended/abducted/externally rotated/supinated position, hold it at the extreme position and wait for the other joints/DOFs to reach their extreme positions as well. As these other joints are being stretched to reach their peak resistance torque (or position) limit, the resistance torque at the first joint(s) which already reaches the torque limit may go beyond the torque limit due to coupling between the joints/DOFs. If the extra torque beyond the specified limit is within a pre-specified range (e.g., 1.5 Nm), the first joint(s) is kept at the held position. Otherwise, the first joint(s) is moved back a bit until the resistance torque is back at the torque limit.

Once all the joints/DOFs reach the extreme extension / supination, hold the arm at the posture for a period of time (e.g., 5 seconds) to let stress relaxation occur and the stiff joints become more compliant.

The arm is moved back towards the initial neutral position and it is held there for a period of time (e.g., 1 sec.), which provides us a measure of arm biomechanical properties at the common position in the stretching process.

Next, the arm is stretched towards the whole arm curled (adducted, internally rotated, flexed and pronated) extreme position. The stretching is controlled similarly as in the case of stretching into the extended, abducted, externally rotated, and supinated extreme positions.

The back and forth stretching process is repeated until a pre-specified stretching period (e.g., 10 minutes) is reached or a stop switch is pushed.

The operator may adjust the stretching limits and stretch at more strenuous levels.

C. With the stiff arm and joints forcefully loosen up by the intelligent stretching carried out in §II-B, the patients is asked to perform voluntary arm reaching tasks involving the shoulder, elbow and wrist of the impaired arm, and they also practice voluntary isolated movement of an individual joint, focusing on the joints with abnormal coupling and loss of individuation identified above in Section II-A.

Motor impairment is associated with both neural and peripheral biomechanical changes. After the intelligent stretching reduces the abnormal joint coupling and stiffness, the neural command may be able to better control the muscles and move the arm. The IntelliArm is made backdrivable so that patients can move the arm with the IntelliArm freely to match or track targets displayed on a computer monitor during the movement training. The movement training is done in the form of computer games to motivate the patients and enhance the motor relearning (Fig. 3).

With the workspace in the horizontal plane determined by diagnosis for an individual patient in Section II-A, a number of target points in the workspace can be displayed and the patient is asked to move the hand from the current position to the target, while matching the individual joint angles as well.

A circle in the virtual hand needs to overlap the red-dot target on the computer monitor for a successful match (Fig. 3). Assistance (or resistance) can be provided by the IntelliArm to the impaired arm during the voluntary movement training when needed. Once a target is reached, it becomes the new current position and a new target in the workspace are displayed for the subject to move to form the new current position (Fig. 3). The shoulder external rotation, flexion, forearm supination can be fixed for simplicity but they can be represented in the figure and matched by the subject if needed. The patients perform the voluntary exercise for about 20 minutes.

For potential further development, as the patient progresses in motor control capability, the workspace is increased and resistance instead of assistance may be provided during the movement to make it more challenging to the patients.

D. To evaluate the outcome in terms of the biomechanical properties and motor-control ability induced by the passive stretching and active movement exercise at the multiple joints involved, including the passive range of motion (ROM) and stiffness at each joint, passive arm ROM, coupling torques/stiffness between the joints/DOFs, active ROM at each joint and coupled movement at the other joints, hand reaching workspace, reaching accuracy and velocity, and muscle strength at each joints and coupled torques at other joints.

D.1. Procedure

For evaluation of the stretching and active movement treatments, a number of biomechanical measures is obtained.
The subject sits upright with the shoulder, elbow and wrist axes aligned with the corresponding motor and long axis of the forearm concentric with the supination circular guide (Fig. 1). The initial position is 60° horizontal adduction for the shoulder, and 60°, 25° and 60° for the elbow flexion, wrist flexion, and forearm supination, respectively (Fig. 1).

At the beginning and end of the treatment, passive stretching is done at matched low terminal torques and slow velocity to evaluate the passive ROM (a direct measure of contracture [3, 30]) and stiffness of each of the joints (shoulder horizontal abduction, elbow and wrist flexion), and cross coupling torques between the shoulder, elbow and wrist. Moving into joint extreme positions manifests the passive mechanical changes in muscles-joints, while the very slow speed controlled by the servomotor minimizes reflex contributions. Reversing the rotation at a common resistance torque level allows objective and accurate comparisons between before and after stretching [27, 31]. The IntelliArm moves one of the joints slowly until a pre-specified resistance torque is reached at this target joint while holding the other joints at their initial positions. Joint angle and multi-axis torques are recorded at the shoulder, elbow and wrist joints simultaneously. The same test is repeated without holding the other joints. The procedure is repeated for each of the multi-joints and multi-DOFs.

III. EXPERIMENTS

A. To evaluate the IntelliArm’s capability of performing patient-specific diagnosis of the passive and active biomechanical changes

Multi-joint and multi-DOF analysis is done on data from the IntelliArm to diagnose the multi-joint biomechanical changes in the impaired arm and evaluate the IntelliArm. For example, which joints and DOFs are coupled abnormally? What are the patterns of abnormal coupling or coactivation? Which joints are stiff? Among the many possible measures, the ROM, stiffness at the shoulder, elbow and wrist, and coupling torques between the three joints are analyzed.

Loss of individuation can be evaluated through multi-joint and multi-DOF analysis. When a subject was asked to do horizontal adduction/abduction of the shoulder without moving the elbow and wrist, for example, a healthy subject could do that successfully (see the blue curve in Fig. 4a), while patients post stroke produced considerable coupled elbow flexion/extension movement. Furthermore, different patients could have different abnormal couplings. On the one hand, the patient with severe impairment (with the stereotypical pattern of adducted shoulder, flexed elbow, flexed wrist and clenched fist, and with control of the shoulder but not the elbow and wrist) showed coupled elbow flexion during shoulder horizontal abduction, indicating stiff elbow flexor muscles. On the other hand, the patient with mild impairment generated elbow extension during shoulder horizontal abduction, suggesting abnormal coactivation of the elbow extensor muscles during the shoulder horizontal abduction. The coupled elbow motion during shoulder horizontal abduction was confirmed by the corresponding elbow flexion torque in a similar task of shoulder horizontal abduction but with the elbow flexion fixed by the IntelliArm (Fig. 4b). Furthermore, during passive movement of the shoulder in horizontal adduction, similar coupling torque was generated in elbow flexion. However, the torque amplitude (~1.8 Nm, not shown here) was much lower than that in Fig. 4b (~14 Nm, the green line), indicating the abnormal coactivation of the elbow flexors (biceps and maybe others as well) during shoulder horizontal abduction was a more significant factor contributing to the coupled elbow torque/motion than the passive stiffness of the elbow flexors. Coactivation of the biceps was corroborated with EMG measurement (Fig. 5). Based on the diagnosis, the different patterns of abnormal couplings should be treated differently in the subsequent passive stretching and active movement therapy. For analysis abnormal coupling, the peak coupling torque is used.

![Fig. 4. Couplings between the shoulder and elbow, showing loss of individuation, with data collected with the 4-DOF arm rehab robot. (a) Coupled elbow flexion/extension when the subject attempted to move his/her shoulder voluntarily in horizontal adduction. The subjects were asked to do horizontal adduction/abduction and the elbow and wrist were free to move. Marked elbow movement was seen in the patients post stroke, suggesting loss of individuation. Data were from a healthy subject (blue) and patients post stroke with mild (red) and severe (green) impairment. (b) A similar shoulder horizontal adduction task performed by the same three subjects but with the elbow and wrist held at their initial positions. Considerable coupling torque was seen at the elbow in the patients post stroke, in the directions consistent with the corresponding elbow joint movement in (a).](image)

![Fig. 5. Couplings between the shoulder and elbow, showing loss of individuation, with data collected with the 4-DOF arm rehab robot. EMG signals from selected muscles and cross-coupling torques at the elbow and wrist during the shoulder horizontal abduction task](image)
shown in Fig. 4(b). Notice the considerable coactivation of biceps and FCR during the active shoulder horizontal abduction.

Abnormal couplings can be similarly analyzed for the distal joints. For example, when the subjects were asked to flex/extension the wrist isolated without moving other joints, the healthy subject could do so successfully (blue line), while the patient with mild impairment generated substantial elbow flexion torque (red line) and the patient with severe impairment (green line) could not move the wrist and generated some torque at the elbow through its coupling with the shoulder (Fig. 6a). Similarly, when the subjects were asked to supinate/pronate the forearm with moving in other joints, the healthy subject could do it successfully. The patient with mild impairment showed substantial coupling torque about the elbow flexion axis (red line) while the patient with severe impairment could not control the forearm twisting (green line) (Fig. 6b).

The limited reaching workspace shown by the patients post stroke (Fig. 7) can be analyzed further at the level of individual joints (Fig. 8) for better understanding of the reduced workspace and potentially guiding therapy. As shown, patients with different degrees of impairment showed different amount of workspace reduction (Fig. 7 and Fig. 8). The reduced workspace for different patients may be due to different changes at the individual joint level, some may be more due to restricted wrist movement and some may be due to combination of the elbow and wrist (Fig. 8). In the 3-D joint space (top-left plot in Fig. 8), the patients had hard time to reach the extended positions. The subject’s reaching data are analyzed to determine the specific joints contributing to the reduced workspace. Similar analysis is done for the workspace during passive movement driven by the IntelliArm.

B. To evaluate stretching and movement training induced changes at the shoulder, elbow and wrist and whole arm

Stretching has been done successfully under intelligent control on patients post stroke with arm hypertonia and stereotypical deformity. Simultaneous shoulder, elbow and wrist stretching is used as treatment to loosen up the stiff muscles-joints of the arms with hypertonia/deformity, while isolated shoulder, elbow or wrist passive movement is used to evaluate the multi-joint dynamics including couplings among the joints.

When the shoulder is stretched back and forth in horizontal abduction with the elbow and wrist held at constant positions, there is a considerable flexion torque generated at the elbow and wrist, following roughly the pattern of the shoulder torque, probably related to the stiff arm muscles crossing the joints (Fig. 9). Compared with healthy subject, the hypertonic arm of the patient post stroke produced several fold higher coupling torques at the elbow (the green line) and wrist (the
red line) joints (Fig. 9). Furthermore, after strenuous stretching of shoulder, elbow and wrist joints simultaneously for about 30 min, the coupling torques at the elbow and wrist when the shoulder is stretched are reduced considerably (Fig. 9b and c).

![Fig. 9. The shoulder was stretched in horizontal abduction at low torque level (about ±3Nm) using the 4-DOF arm rehab robot. Joint torques at the shoulder (blue), elbow (green) and wrist (red) during the shoulder stretching from a healthy subject (a) and a patient post stroke with considerable arm hypertonia/deformity (b and c) are shown. For the patient, joint torques from similar stretching trials at the beginning and end of the stretching session are shown in (b) and (c), respectively.](image)

Stretching-induced improvement can be analyzed and shown clearly in 3-D joint space, with the shoulder, elbow and wrist stretched simultaneously (Fig. 10a). For further detail during the stretching including the stretching-induced improvement, the kinematic and kinetic data can also be shown together as function of time (Fig. 10b). The IntelliArm stretched arms with hypertonia/deformity strenuously and safely, and patients post stroke like the stretching and feel it loosen their stiff arms. Some relevant analysis results are given here. For examples, paired t-test showed that both the elbow extension (P=0.01) and flexion (P=0.03) ROMs measured at controlled resistance were improved significantly after the strenuous stretching. With the same subjects, wrist extension also increased significantly with P=0.002 (paired t-test). Wrist flexion did not change considering that the wrists were hypertonic and deformed in flexion.

The strenuous and yet safe stretching loosen the stiff joints and make them significantly less stiff. At comparable joint positions, both elbow extension (P=0.005) and flexion (P=0.042) stiffness are reduced after a session of strenuous stretching. Wrist joint stiffness is also reduced significantly in both extension (P=0.024) and flexion (P=0.044) (paired t-test).

![Fig. 10. (a) The shoulder, elbow and wrist passive ROMs (passive workspace) from a patient post stroke with considerable arm hypertonia/deformity, determined using the 4-DOF arm rehab robot and shown in 3-D joint space. (b) Stretching data from a stroke patient with substantial hypertonia/deformity at the elbow and wrist. The elbow and wrist of a stroke patient with arm deformity and hypertonia were stretched simultaneously using the IntelliArm. The left and right columns correspond to data from the elbow and wrist, respectively. The 1st and 2nd rows show the elbow and wrist flexion angles and elbow and wrist flexion torque (elbow and wrist flexor resistance torque was negative) as functions of time. The 3rd row shows the torque-angle curve at the two joints and the slope of the curves corresponds to the joint stiffness. The blue dashed line and red solid line correspond to data at the beginning and end of a stretching session, respectively.](image)

With the strenuous stretching loosening the stiff joints, the CNS may be able to control the muscles and move the joint more properly. During the active wrist extension, a patient with difficulty extending the wrist voluntarily (left column of Fig. 11) could control it more easily and moved it further into wrist extension after stretching (right column of Fig. 11). The improvement may be due to reduced co-contraction of wrist flexors as well as improved control of the wrist extensors. The flexor/extensor co-contraction ratio during the extension task was reduced from 29.6% to 20.0% (Fig. 11). Wrist extension MVC of the subject was similarly improved, partly due to the reduction in co-contraction.

![Fig. 11. Voluntary wrist extension before (left column) and after (right column) stretching with reduced flexor-extensor co-contraction.](image)

**IV. DISCUSSIONS AND CONCLUSIONS**

Impairments in patients post stroke usually involve the shoulder, elbow and wrist simultaneously. Patients may develop spastic hypertonia and reduced range of motion (ROM) at the multiple joints with abnormal couplings between the multiple joints and between the multiple degrees of freedom (DOF) (e.g., elbow flexion and forearm pronation) at a joint. They may lose independent control of individual joints (loss of individuation) and coordination among the joints. There is a strong need to evaluate and treat the shoulder, elbow and wrist joints of impaired arms in well coordinated ways according to the multi-joint and multi-DOF pathological changes. However, it is not practical for a clinician to evaluate the multi-joint and multi-DOF properties including couplings and interactions simultaneously and quantitatively, although the information may be very useful in...
guiding therapy of the arm. On the other hand, existing rehabilitation robots usually treat a single joint or the whole arm without controlling/evaluating the individual joints/DOFs specifically and treating them based on the conditions of the individual joints/DOFs and couplings among the joints/DOFs. Furthermore, contracture often develops in arms with hypertonia/deformity and muscles-joints may become too stiff to follow the CNS commands, especially in chronic patients post stroke. Strenuous stretching to loosen up the stiff muscles-joints followed by voluntary movement training may improve motor function recovery for those patients with limb hypertonia/deformity.

Our study uses a new whole-arm intelligent rehabilitation robot (Arm Stretcher) capable of controlling the shoulder, elbow, and wrist individually and simultaneously, which may help achieve effective stroke rehabilitation based on the following features incorporated into the same device: 1) it has unique diagnostic capabilities for individual patients including information on which joints and which DOFs have significant changes in the neuromechanical properties, which joints lose independent control, what are the abnormal couplings, and whether the problem is due to passive muscle properties or active control capabilities? 2) based on the diagnosis, it stretches the hypertonic/deformed joints of the patients post stroke under intelligent control to loosen up the specific stiff joint(s) or to break up abnormal couplings between joints/DOFs so that the CNS can potentially control the relevant muscles and joint movement more effectively; 3) with the stiff joints loosened up, the patients practice voluntary reaching tasks to regain/improve their motor control capability; and 4) the outcome is evaluated quantitatively at the levels of individual joints, multiple joints/DOFs, and the whole arm.

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