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# Multi-Joint Assessment of Proprioception Impairments Post Stroke

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## Abstract

**Objectives:** To investigate shoulder, elbow and wrist proprioception impairment post stroke.

**Design:** Proprioceptive acuity in terms of the threshold detection to passive motion at the shoulder, elbow and wrist joints was evaluated using an exoskeleton robot to the individual joints slowly in either inward or outward direction.

**Setting:** A university research laboratory.

**Participants:** Seventeen stroke survivors and 17 healthy controls. Inclusion criteria of stroke survivors were 1) a single stroke; 2) stroke duration <1 year; and 3) cognitive ability to follow simple instructions.

**Interventions:** Not applicable.

**Main Outcome Measures:** Threshold detection to passive motion and detection error at the shoulder, elbow and wrist.

**Results:** There was significant impairment of proprioceptive acuity in stroke survivors as compared to healthy group at all three joints and in both the inward (shoulder horizontal

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Disclosure

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adduction, elbow and wrist flexion, $p<0.01$) and outward ($p<0.01$) motion. Furthermore, the distal wrist joint showed more severe impairment in proprioception than the proximal shoulder and elbow joints post-stroke ($p<0.01$) in inward motion. Stroke survivors showed significantly larger detection error in identifying the individual joint in motion ($p<0.01$) and the movement direction ($p<0.01$) as compared to the healthy group. There were significant correlations among the proprioception acuity across the shoulder, elbow and wrist joints and two movement directions post stroke.

**Conclusions:** There were significant proprioceptive sensory impairments across the shoulder, elbow and wrist joints post-stroke, especially at the distal wrist joint. Accurate evaluations of multi-joint proprioception deficit may help guide more focused rehabilitation.

### Keywords

Proprioceptive acuity; kinesthesia; sensory impairment; stroke

## Introduction

Lesions of the central nervous system in stroke patients may not only induce motor function impairment but may also cause loss of the somatosensory function in both peripheral and central regions. Thus, stroke-induced somatosensory impairment can negatively impact activities of daily living [1-4]. The somatosensory system provides information about the joint position and movement in 3-dimensional space, which directly affects motor learning and control in rehabilitation [5, 6].

Proprioception of a single joint has been examined in previous studies, including increased shoulder proprioception post stroke [7], knee proprioception post ACL injury and reconstruction [8], and wrist proprioception in flexion/extension, abduction/adduction and supination/pronation [9]. Semrau et al. examined two sub-modalities of proprioception in terms of position sense and kinesthesia, evaluated at the index fingertip of stroke survivors, and reported proprioception deficits in both sub-modalities (position sense and kinesthesia) [10]. However, there is a lack of investigation of proprioception across multiple individual joints within a limb, which plays a significant role in locating the movement of each segment. Knowledge of impairment at each of the individual joints is important in understanding the sensory deficit post stroke and developing impairment-specific treatment. There has been a lack of evaluation tools and characterizations of proprioception at the multiple individual joints in the upper limb in stroke survivors [11].

Considering that human functional activities involve multiple individual joints moving simultaneously in the upper limb, examination and treatment of multiple joints are functionally relevant. An upper-limb exoskeleton robot called IntelliArm was used for multi-joint passive-active sensory-motor assessment post stroke [12]. The multiple-joint proprioception acuity was determined with the threshold detection of passive motion (TDPM), the threshold angle when the participant felt the subtle movement, under an imposed movement at the shoulder, elbow, or wrist [11]. TDPM is assessed through robot-controlled slow movement, not dependent on the participant's movement ability. Thus, the purpose of this study was to investigate the impairment of proprioceptive acuity across multiple joints (shoulder, elbow, and wrist) of the upper extremity using a custom multi-joint exoskeleton robot on stroke survivors. The study may help us gain insights into the shoulder, elbow, and wrist sensory deficits post stroke and guide impairment-specific rehabilitation post stroke.

## Methods

### Participants

Seventeen stroke survivors (mean (SD): 54 (7.29) years old, 11 males and 6 females) and 17 sex-matched healthy group (mean (SD): 48.36 (13.9) year old, 11 males and 6 females) participated in this study. Inclusion criteria of patients post stroke were 1) diagnosis of a single stroke (hemiplegic with a stable medical condition); 2) stroke duration within one year; and 3) cognitive ability to follow simple instructions. The exclusion criteria included 1) participant had severe pain in the upper extremity; 2) the participant had severe contracture in the upper extremity joint; 3) the participant had severe cardiovascular conditions and were unable to participate in the experiment duration; 4) the participant had unrelated musculoskeletal injuries. Participants were encouraged to ask any questions. All participants signed an informed consent form approved by the Institutional Review Board.

After enrollment, clinical evaluations were done on each stroke survivors to obtain their Motor Status Scale and Modified Ashworth Scale at the elbow and wrist [13, 14].

### Experimental Setup

An exoskeleton robot called IntelliArm was used to control shoulder horizontal adduction-abduction, elbow flexion-extension, and wrist flexion-extension movements (Fig. 1) [11, 12]. For individual participants, the IntelliArm was adjusted to align the robotic shoulder, elbow and wrist axes with the corresponding shoulder, elbow and wrist axes of the human participant.

### Procedures for Proprioception Assessment

The hemiparetic arms of the stroke survivors were tested. The dominant arm of the healthy group was selected. Participants were seated on an adjustable chair. Their upper arm and forearm were strapped to the corresponding braces to ensure well-alignment at each joint throughout the experiment. The participant's palm was held by a hand brace. The initial position of the testing arm was 70° shoulder horizontal adduction, 60° elbow flexion, and 0° wrist flexion. Each participant sat upright comfortably with the arm attached to the IntelliArm (Fig. 1). The participants were instructed to close eyes and not to look at the joints during the test. The testing orders of each participant's shoulder, elbow, and wrist joints were randomly selected. Each joint was moved 3 times in each of the two directions (shoulder horizontal adduction and abduction, elbow/wrist flexion and extension) at each joint. A slow movement speed of 0.5 °/s was used. The participant was instructed to press a hand-held switch as soon as he/she felt a joint movement, and to state which joint was moved and in which moving direction [7, 11, 15]. The IntelliArm moved back to the initial position after the participant pressed the switch and waited for the next trial.

### Data Analysis

Our initial arm posture setup included the shoulder positioned at 70° horizontal adduction, elbow at 60° flexion, and wrist at 0° flexion before the imposed movement. A joint was moved by the robot slowly during each testing trial, starting at a time unknown to the participant. When the subject felt the movements, he/she pushed the switch and stated which joint was moved and in which direction. Once the participant clicked the switch, indicating their perception of joint movement, the robotic arm would halt the imposed motion on that specific joint. Thus, the difference between the initial angular position and the final angular position when the switch was pushed represents the angular value used to assess proprioceptive acuity in our testing results (so called TDPM). Proprioceptive acuity was measured quantitatively as the angular threshold detection of passive motion [7, 11, 15, 16]. A successful trial was counted when the participant detected the joint motion and the direction of the motion. Detection errors were defined for either joint or direction errors which were evaluated with percentage of totally tested trials for each participant. If the participants had no detection of movement, the low joint movement stopped at a maximum of 30° for the shoulder and elbow movement and at 45° for the wrist movement, those trials were considered for loss of proprioception, which were also evaluated with the percentage of failure trials for some participants.

Three-way repeated measure analysis of variance (ANOVA) with the group, direction, and joint as the 3 factors and 2×2×3 corresponding levels was used to evaluate differences in proprioceptive acuity between the two groups (stroke and healthy), two directions (inward and outward) of joint motion, and across three joints (shoulder, elbow, and wrist), with a significance level $p < 0.05$.

Correlations among proprioceptive acuity across the shoulder, elbow, and wrist were examined in stroke survivors. With each joint involving the inward and outward directions, Pearson correlation coefficients among the six proprioception measures including the inward and outward directions at the shoulder, elbow and wrist were calculated.

## Results

### Threshold of Detection at the Shoulder, Elbow, and Wrist

There was significant impairment of proprioceptive acuity post stroke as compared to the healthy group [$F(1,16)=16.367$, $p = 0.001$] (Figs. 2A & 2B). During the passive outward movements by the exoskeleton, the stroke group showed poorer proprioception with larger TDPM at the shoulder ($p = 0.001$), elbow ($p = 0.001$), and wrist ($p = 0.001$) as compared to the healthy group (Fig. 2A). Similarly, the results showed impaired proprioception of the stroke group with larger TDPM during passive inward motion at the shoulder ($p = 0.007$), elbow ($p = 0.001$), and wrist ($p = 0.001$) (Fig. 2B).

There were no significant differences in the proprioceptive acuity between the imposed inward and outward motions for either the stroke ($p = 0.349$) or healthy control group ($p = 0.712$), indicating similar TDPM between the inward and outward directions of passive movements within each group.

Comparing across the joints, there were significant differences in joint proprioceptive acuity among the joints during passive inward motion in the stroke survivors [$F(2, 15) = 8.367$, $p=0.004$] (Fig. 3). Further pairwise comparison of proprioceptive acuity showed that proprioceptive acuity at the wrist was worse than the shoulder ($p = 0.001$) and worse than the elbow ($p = 0.003$), whereas there was no significant difference in proprioceptive acuity between the shoulder and elbow joints ($p = 0.641$). During the imposed outward motion, there were no significant differences in proprioceptive acuity among the joints in the stroke group [$F(2, 15) = 0.155$, $p = 0.857$; Table 1]. In the healthy group, there were no significant differences in proprioceptive acuity among the three joints within either inward or outward motion (Fig. 3B).

## Detection Errors at the Shoulder, Elbow, and Wrist

Not only did stroke survivors demonstrated impaired proprioception with larger TDPM at the individual joints, but they also often identified the wrong joint and/or the wrong direction of joint movement. The detection error in identifying the individual joint in motion was significantly larger for the stroke survivors as compared to the healthy group [$F(1, 20) = 17.361$, $p = 0.001$] (Fig. 3) , and then the detection error in identifying the motion direction was also significantly larger in stroke survivors than those in the healthy group [$F(1,20) = 11.21$, $p = 0.003$] (Fig. 3).

The detailed test results are shown in Table 2. For each of the shoulder, elbow, and wrist joints, there were significantly larger errors for the stroke survivors both in identifying the joint moved by the robot and in identifying the direction of the joint motion ($p < 0.05$).

For the stroke survivors, there were significant differences in the detection error for inward and outward motion between the shoulder joint and wrist joint ($p = 0.023$), but no significant differences between the shoulder joint and elbow joint ($p = 0.455$) and between the elbow joint and wrist joint ($p = 0.256$) for the detection error.

## Loss of Proprioception at the Upper Extremity

Four of 17 participants from stroke survers had severely impaired proprioception at the shoulder, elbow and/or wrist joints in this study. They had no detection responses throughout some trials of slow joint movement (Fig. 4). Patient P1 did not detect any elbow movement throughout the maximum 30 degree slow movement and across the multiple trials (100% at the elbow in Fig. 4). Patient P2 detected the shoulder and elbow movement but failed to detect the wrist movement in some trials (Fig. 4). Patient P4 detected the elbow movement but failed to detect the shoulder and wrist movement in some trials. This indicated their partial deficits of proprioception at the joints with large proprioception threshold.

## Correlations of TDPM across the Shoulder, Elbow, and Wrist

Pearson correlation coefficients among the inward and outward proprioception acuity across the shoulder, elbow, and wrist of the stroke survivors are shown in Table 3. There were significant correlations between all the pairs of correlations ($p < 0.01$) except for the correlation between the wrist inward and outward movements ($p = 0.069$).

### Clinical Scales on the Shoulder, Elbow and Wrist Post Stroke

As a clinical measure similar to the Fugl-Myer scale but with expanded measuring components (total 82 points), the Motor Status Scale showed significant motor impairment of the stroke survivors (Table 4). The proximal portion score for the shoulder and elbow was 24.6±9.1, corresponding to 61.5±22.7% of the total 40 points. The distal portion score for the wrist and hand was 15.8±13.6, corresponding to 37.7±32.4% of the total 42 points. This indicated the distal wrist and hand were more severely impaired than the proximal shoulder and elbow joints.

The MAS showed considerable spasticity at the evaluated elbow and wrist joints (Table 4). The elbow and wrist flexor muscles had a trend of higher spasticity than the corresponding extensor muscles, as indicated by the MAS scores (Table 4).

## Discussion

Most rehabilitation therapies target motor recovery to improve muscle strength, movement control, and coordination. However, sensory reintegration is implied but generally not emphasized [17]. Treatment strategies using robotic devices are usually for simulating manual therapy and assisting in patient's action, and giving appropriate feedback in guiding motor relearning [18]. As seen in overviewing our participants of stroke survivors in this study, some of the stroke survivors not only had impaired motor function but also showed sensory deficits. Impaired somatosensory function affects daily activities [19]. The proprioceptive system, including position and movement sense, helps detect the joint angular position and provides both feedforward and feedback information, which is helpful for motor learning and control [20]. Therefore, the somatosensory aspect of assessment and rehabilitation training in stroke survivors should be considered for rehabilitation intervention of both sensory and motor management.

This study showed that the stroke survivors had impairment of somatosensory functions at the upper extremity. The proprioception results were significantly different between stroke and healthy groups during controlled slow movement at the shoulder, elbow, or wrist joint. The post-stroke proprioception impairment characterized in this study included specific impairment at the shoulder, elbow, and/or wrist with (1) reduced proprioceptive acuity (increased threshold joint angle); (2) detection error on the movement direction; and (3) loss of proprioception (no detection even at the largest motion). The proprioception changes in the stroke survivors varied with a large standard deviation, indicating some stroke survivors with minor proprioceptive deficits and others with severe proprioception impairment. Four out of the 17 stroke survivors had severely impaired position and movement sense at the joints and could not tell if the shoulder, elbow, or wrist joint was moving, which was Condition (3) listed above. Those different patterns of proprioception impairment indicate that stroke could affect sensory as well as motor system to various degrees post stroke. Those varying degrees of proprioceptive deficits from the different stroke participants might be related to different locations of brain lesions, such as the thalamus [21, 22], posterior limb of the internal capsule [23], and posterior parietal cortices [24, 25]. These different impairment conditions should be considered in the treatment management for individual stroke survivors.

In a survey of 102 inpatients with hemiparesis following first stroke from a previous study, somatosensory loss was characterized with no significant difference in proprioception acuity between the proximal and distal joints found [26]. In this study, we found that there were not only significant differences in proprioceptive acuity at all three joints of the arm between the stroke and healthy groups, but also differences between the proximal and distal joints in the stroke survivors during inward movement. The wrist proprioceptive acuity was more impaired than that of the shoulder and elbow post stroke. In general, stroke survivors tend to have more severe impairment at the distal joints of wrist and hand than at the proximal joints of shoulder and elbow. The stroke survivors in this study, for example, had the wrist/hand portion of MSS at 37.7% of total 42 points while their shoulder/elbow portion of MSS was at 61.5% of the total 40 points. The more severe motor impairment at the distal joints compared to the proximal joints may be associated with the more severe sensory impairment at the distal joints than at the proximal joints.

Treatment planning should take sensory impairment across the multiple joints in the arm into consideration. The large variations in proprioception acuity at the three joints of the stroke group in Fig. 2 above indicates varying levels of proprioceptive impairment across the stroke survivors and across the joints. It suggests that individualized treatment should be applied to stroke survivors based on accurate multi-joint proprioception evaluations as reported in this study. One of the treatment strategies is to combine strong sensory-stimulating stretching and active movement training as done in our previous studies, which facilitated sensory-motor recovery in individuals with upper-extremity sensory-motor impairment [27-29].

There are different types of proprioceptive evaluations. Assessment approaches of the joint position matching (JPM) or joint position reproduction focus on matching and reproduction in the active movement of a relatively long range of motion [9, 30-32]. These active movement tasks could be difficult for stroke survivors with severe motor impairment. The TDPM used in this study applied a robot-controlled joint movement to evaluate proprioceptive acuity at the impaired limb, and the patients just need to focus on detecting any joint motion and identifying the joint moved and the direction of movement. Therefore, it is an appropriate assessment for multiple-joint evaluations in stroke survivors, including those with severe motor impairment. The upper limb motion often involves multiple segment activities. Comparing to evaluations of proprioception of a single joint, multi-joint proprioception evaluations may help understand coupling impairment across multiple joints and contributions of specific individual joints to proprioception deficiency, which could potentially guide more focused and effective treatment for stroke survivors. A systematic review reported that proprioceptive training are helped and joint position and target-reaching training consistently enhanced joint position sense by up to 109% [33].

## Study Limitations

First, the sample size of this study was relatively small. Further studies are needed (and are ongoing) to validate the results further. Second, location of lesion was not investigated in this study. Considering potential relationships between location of brain lesion and various types of sensory impairment, lesion location should be considered in future studies.

## Conclusions

Stroke survivors had significantly reduced proprioception acuity with much larger proprioception threshold angles at the shoulder, elbow and wrist than their counterparts of healthy group. The distal joint demonstrated more severe proprioception impairment than the proximal joint. Multi-joint proprioception characterizations help understand sensorimotor deficits of individual joints post stroke and plan subsequent targeted, individualized neurorehabilitation.

## Acknowledgment

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## Abbreviations

| | |
|---|---|
| **ANOVA** | Analysis of variance |
| **TDPM** | Threshold detection of passive motion |
| **JPM** | Joint Position Matching |

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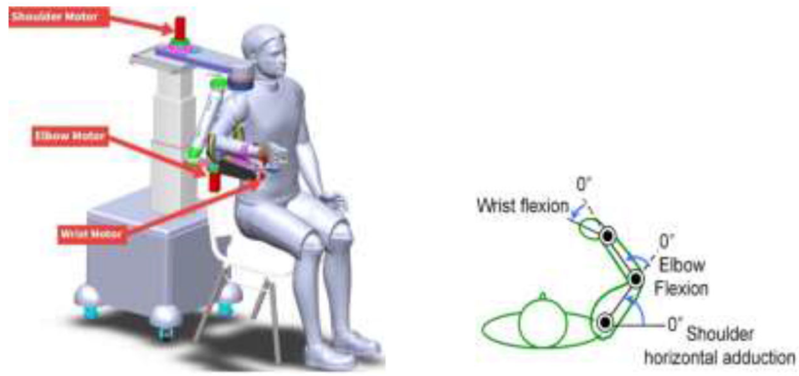


(a) (b)

**Figure 1.**
Experimental setup for the proprioception evaluations. (a) The participant was seated with the arm and forearm strapped and held onto the corresponding braces to ensure proper joint alignment during the experiments. The elbow and wrist flexion axes were aligned with the corresponding elbow and wrist motor axes, respectively. The shoulder motor drove subject's shoulder through a timing-belt transmission mechanism with the driving axis aligned with the shoulder horizontal adduction. The initial position was 70° shoulder horizontal adduction, 60° elbow flexion, and 0° wrist flexion (b).

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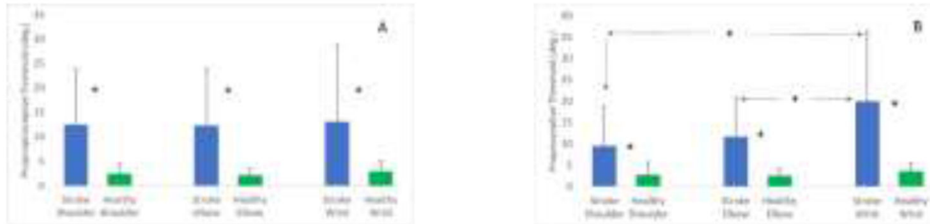

(a) (b)

**Figure 2.**

Comparison of proprioceptive acuity at the shoulder, elbow, and wrist between the stroke and healthy groups. (A) is for the imposed outward movement at the shoulder (h-abduction), elbow (extension), and wrist (extension). (B) is for the imposed inward movement at the shoulder (h-adduction), elbow (flexion), and wrist (flexion). The blue and green bars correspond to the mean proprioception acuity of the stroke and healthy group, respectively. The symbol * indicates significant differences between the two groups at the shoulder, elbow, and wrist in the inward or outward directions.

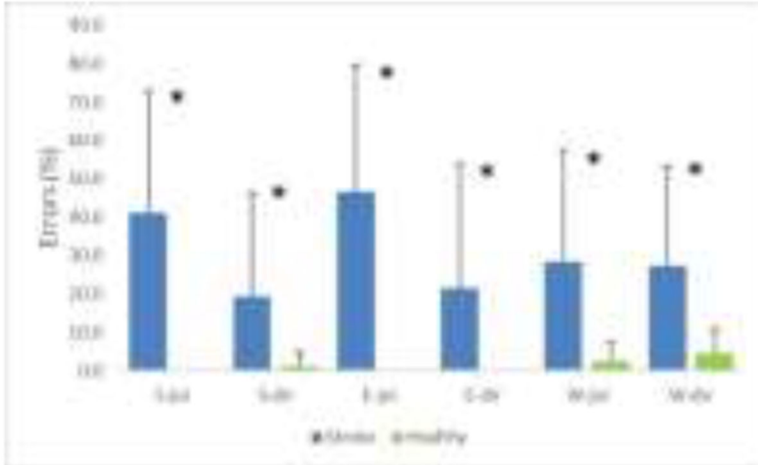

**Figure 3.**

The movement detection error percentage (mean and standard deviation) among all the trials for each of the tasks of detecting the imposed movements at the shoulder, elbow, and wrist joints and movement directions in the stroke and healthy groups respectively. * S-joi = shoulder joint; S-dir = shoulder movement direction; Elbow-joi = elbow joint; Elbow-dir = elbow movement direction; W-joi = wrist joint; W-dir = wrist movement direction.

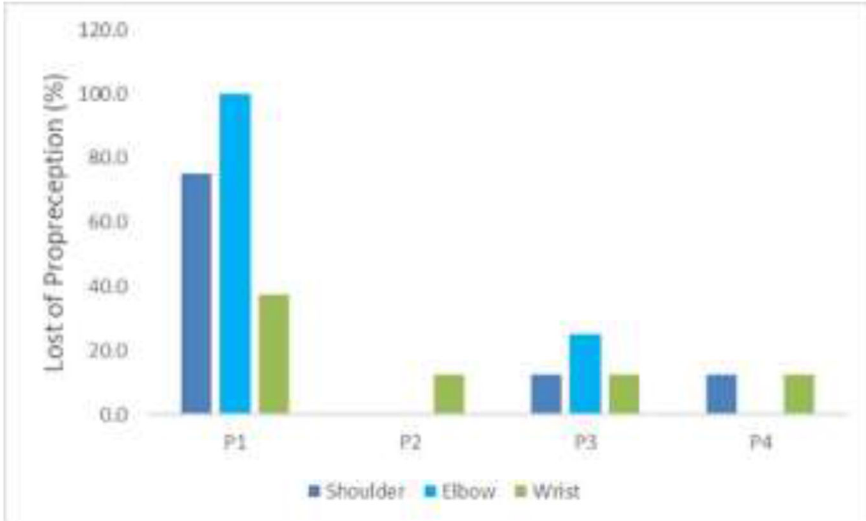


**Figure 4.**
Lost of proprioception from four patients post stroke (P1, P2, P3, P4) at the shoulder, elbow, and/or wrist joints.

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**Table 1.**

Comparisons of Proprioception Acuity between the Stroke and Healthy Groups

| Tested Joint | Joint movement | Stroke (°) | Healthy group (°) |
|---|---|---|---|
| **Shoulder** | Horizontal Abduction | 12.5 (±11.4) | 2.5 (±1.9) * |
| | Horizontal Adduction | 9.6 (±9.2) | 2.7 (3.0) * |
| **Elbow** | Extension | 12.3 (±11.7) | 2.2 (±1.3) * |
| | Flexion | 11.7 (±9.1) | 2.6 (±1.8) * |
| **Wrist** | Extension | 13.1 (±15.7) | 2.9 (±2.3) * |
| | Flexion | 19.9 (±16.4) | 3.5 (±1.9) * |

* Statistical significance between the groups with $p < 0.01$

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## Table 2.

Comparison of Detection errors (%) between the Stroke and Healthy Groups

| Joint Moved | Identification error | Stroke (%) | Healthy (%) |
|---|---|---|---|
| **Shoulder** | Joint | 41.0 ±32.0 | 0.0 ±0.0 * |
| | Direction | 19.3 ±27.0 | 1.1 ±3.8 * |
| **Elbow** | Joint | 46.6 ±33.1 | 0.0 ±0.0 * |
| | Direction | 21.6 ±32.2 | 0.0 ±0.0 * |
| **Wrist** | Joint | 28.4 ±29.1 | 2.3 ±5.1 * |
| | Direction | 27.3 ±26.1 | 3.4 ±5.8 * |

Detection error shown as mean ± standard deviation, in percentage at each joint. *Statistical significance between groups with $p < 0.05$.

**Table 3.**

Correlations of Proprioceptive Acuity across the Shoulder, Elbow and Wrist Post Stroke

| | S_ab | E_e | W_e | S_ad | E_f | W_f |
|---|---|---|---|---|---|---|
| **S_ab** | 1 | | | | | |
| **E_e** | .714** | 1 | | | | |
| **W_e** | .800** | .651** | 1 | | | |
| **S_ad** | .891** | .854** | .772** | 1 | | |
| **E_f** | .754** | .920** | .544* | .829** | 1 | |
| **W_f** | .689** | .840** | 0.452 | .729** | .856** | 1 |

Notes: S_ab = shoulder abduction, E_e = elbow extension, W_e = wrist extension, S_ad = shoulder adduction, E_f = elbow flexion, W_f = wrist flexion. * and ** indicate $p<0.05$ and $p<0.01$, respectively.

**Table 4.**

Motor Status Scale and Modified Ashworth Scale of Stroke Survivors

| Clinical Scale | | Score | % |
|---|---|---|---|
| **Motor Status Scale (MSS)** | Shoulder-elbow (40) | 24.6 (±9.1) | 61.5 ± 22.7 |
| | Wrist-hand (42) | 15.8 (±13.6) | 37.7 ± 32.4 |
| | Total (82) | 40.4 (±22.3) | 49.3 ± 27.2 |
| **Modified Ashworth Scale (MAS)** | Elbow flexion (0-4) | 2.4 (±0.7) | |
| | Elbow extension (0-4) | 1.5 (±0.6) | |
| | Wrist flexion (0-4) | 2.3 (±0.6) | |
| | Wrist extension (0-4) | 1.3 (±0.3) | |