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Arm Motion Analysis of Stroke Patients in Activities of Daily Living Tasks: A Preliminary Study

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***Abstract*—Analyzing activities of daily living (ADL) for the development of practical upper limb rehabilitation robots is challenging in stroke patients. Basic ADL tasks using an upper limb are defined based on clinical assessment tools. The motions of 8 healthy participants and 8 stroke patients were recorded during defined ADL tasks, and then analyzed with respect to completion time, linearity of motion, and range of motion of the joints. Completion time and motion trajectories were significantly different between stroke subjects and healthy participants. For tasks involving the transfer of an object from a table to the user's mouth, wrist radial–ulnar deviation motions should be taken into account while designing robots for gross movements via elbow and shoulder joints. Our findings can be extended to the design of trajectories of rehabilitation robots as well as of simplified robots.**

I. Introduction

TASK-oriented training [1] is an important factor for the development of successful rehabilitation robots. The training chiefly includes activities of daily living (ADL) tasks, which are basic tasks of everyday life, such as eating, drinking, dressing, bathing, toileting, and transferring. ADL tasks are strongly related to the interaction between the user's upper limbs and the environment. In case of upper limb rehabilitation robots, ADL task-based training provides the user with therapeutic effects as well as strong usage motivation. Rehabilitation robots aid in the functional recovery of disabled people and encourage their return to society. These rehabilitation robots can provide—consistently and repetitively—high-quality rehabilitation training. The primary users of upper limb rehabilitation robots are stroke and spinal cord injury patients.

The upper limbs are responsible for a variety of motions during ADL via various joints including the wrist, elbow, and shoulder. The performance of ADL tasks depends on the range [2], time, and trajectory of the upper limb movements. The analysis of these parameters could be used to design simple but effective robots for performing ADL tasks. In addition, actual ADL trajectories of the robots could be built on the basis of the motion patterns of disabled people. Robots for upper limb movements include the end-effector system and the exoskeleton system. Bridging ADL tasks and rehabilitation is an attractive object of study.

Robot-aided therapy devices are being utilized in the physical and neurological rehabilitation of persons after stroke. Robot-assisted therapy revealed evidence of potential long-term benefits of intensive rehabilitation [3]. In accordance, robot-assisted therapy significantly improves upper limb motor function after stoke [4]. On the other hand, Mehrholz et al. found that electromechanical-assistive devices in rehabilitation settings do not ameliorate ADL despite improvements in arm function and strength [5]. The upper extremity motions of healthy subjects during selected ADL tasks were quantitatively analyzed to determine the minimal requirements for the performance of a subset of ADL [2]. However, the upper extremity motions of stroke survivors have not yet been quantitatively analyzed. It has been reported that a robot-assisted training system in three-dimensional space is not sufficient for this analysis [6]. In this regard, robots have been designed under the knowledge of the joint kinematics and moments during ADL tasks [7]. Especially, a cost-effective robotic system should consider the mechanism of ADL tasks. The study of ADL tasks ultimately contributes to the systematic development of rehabilitation robots.

In this paper, we compare ADL tasks between stroke patients and healthy participants. At first, we defined 12 ADL tasks for stroke patients in three-dimensional space on the basis of clinical assessment tools. A motion capture system was used to record the upper limbs motions of 8 stroke participants and 8 healthy participants. The task completion time, trajectories, and range of motions were also determined. Our findings potentially contribute to the systematic development of rehabilitation robots equipped with customized training protocols for stroke survivors.

II. Experimental Methods

A. Definition of ADL Tasks

Clinical assessment tools were used to evaluate the upper limb motor function and define ADL tasks. Five clinical assessment tools were selected based on the literature: the Motor Activity Log (MAL) [8], Wolf Motor Function Test (WMFT) [9], Motricity Index [8], Action Research Arm Test

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(ARAT) [10], and Fugl–Meyer Assessment (FMA) [9]. These 5 clinical assessment tools are used as the typical assessment tools related to self-care domain of function skills scale in upper extremity after stroke. The performance items of Functional Independence Measure (FIM) and Modified Barthel Index (MBI) are mainly related to mobility domain of ADL [11]. Therefore, these assessment tools did not use in this study. However, it will be considered in future work. In particular, MAL and WMFT are related to ADL [12, 13]. The number of tasks was 109, including 30 tasks in the MAL, 17 tasks in the WMFT, 10 tasks in the Motricity Index, 19 tasks in the ARAT, and 33 tasks in the FMA. We classified the specific evaluation tasks in accordance with movement mechanisms, directions, and task heights with respect to subjects. Among all the classified tasks, we have extracted 12 tasks that are strongly related with ADL in the upper limbs (Table 1). We assumed that all of the tasks were performed by the dominant arm of healthy participants or the affected arm of stroke subjects in a sitting position, as shown in Fig. 1.

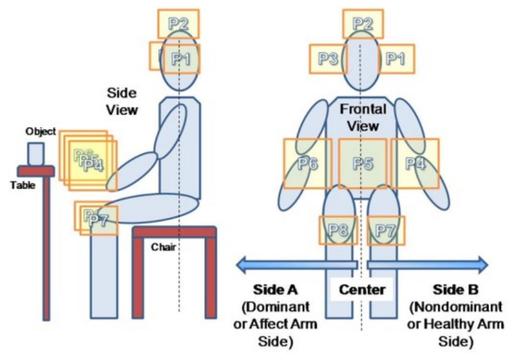

Fig. 1. Position information of defined tasks.

TABLE I
THE DEFINED 12 ADL TASKS

Task#	Pos	Level	Dir	Tasks
1	P1	H	B	Arm reaching to an ear of side B
2-1	P2	H	C	Arm reaching to a top of a head
2-2	P2	H	C	Eat with a spoon (reaching to a mouth)
2-3	P2	W	C	Drinking with a cup
3	P3	W	A	Arm reaching to an ear of side A
4-1	P4	W	A→B	Moving an object from side A to side B
4-2	P4	W	B→C	Moving an object of side B to the center
5	P5	W	C	Pull an object
6-1	P6	W	B→A	Moving an object from side B to side A
6-2	P6	W	A→C	Moving an object of side A to the center
7	P7	K	B	Arm reaching to a knee of side B
8	P8	K	A	Arm reaching to a knee of side A

Abbreviations: Pos = Position; Level = the level (height) in which tasks performed; Dir, Direction; H = Head; W = Wrist; K = Knee; A = Side A (dominant or affected arm side); B = Side B (nondominant or healthy arm side); C = Center. The weight of an object is 500 g.

B. Motion Analysis of ADL Tasks

Eight healthy participants (age [mean ± standard deviation], 28.9 ± 1.3; 7 men, 1 woman) and 8 stroke patients (age, 53.1 ± 9.1; 7 men, 1 woman) were selected for this study. The Institutional Review Board of the National Rehabilitation Center of Korea approved the study protocol. Table 2 shows the data of the stroke patients who participated in this study.

The upper limb movements during ADL tasks were recorded by an optical motion capture system (VICON system; Oxford’s Metrics, Oxford, UK) with 8 infrared cameras at a sampling frequency of 120 Hz. Reflective markers were placed on anatomical points of the different segments (the seventh acromioclavicular joint, medial and lateral epicondyle, ulnar and radial wrist, left third metacarpus, and lateral forearm) of the upper dominant side (healthy participants) or the affected side (stroke patients). The non-dominant affected side of stroke patients was examined to better understand the consequences of stroke on ADL tasks.

TABLE II
STROKE SUBJECT DATA

Age/Sex	Affected side	Duration (yr)	MMSE (30)	FMA U(66)	Brunnstrom Stage
70/M	Right	9	30	65	6
69/M	Right	8	28	66	6
51/M	Left	7	27	17	6
65/M	Left	14	29	65	6
63/F	Left	5	27	66	6
15/M	Right	0.5	30	66	5
45/M	Left	0.8	29	66	5
47/M	Left	0.8	30	64	5

We used mechanical switches under the hand and the target to accurately determine starting and finishing time. Some tremor or spasticity was found during ADL task motion of stroke subjects. Thus, mechanical switches effectively detected starting and finishing time in comparison with velocity profiles of motion captured data. All the subjects performed the 12 tasks described in Table 1. The subjects who participated in this experiment were asked to find a comfortable sitting position on a straight back chair in front of a table while the testing arm pronated with the hand resting on a table and the other arm rested on the lap (Fig. 2). When ready, the subject started the tasks at a comfortable self-selected speed. Every subject performed at least 3 trials in 1 testing session.

Measures of upper extremity performance derived from step-response and phase-plane analysis techniques were evaluated during the Random-Step Arm-Tracking task that was performed in 1 dimension of planar movement using a joystick [14]. In our study, 12 ADL tasks of the upper limb were performed point-to-point movements in three-dimensional spaces. The accurate curve paths of an arm were analyzed to evaluate the quantitative characteristics of the hemiplegic side of stroke patients. Each ADL task was divided into 2 or 3 phases. For example, one the tasks consisted of the following phases: moving toward a target, manipulating a target, and returning from a target. The curvilinearity ratio (CR) [15], movement completion time, and the range of motion (ROM) of each joint were calculated in every phase of each ADL task to analyze the motion of the upper limb. The CR represents the ratio between a straight line and the actual displacement from start to target at the finger marker of a moving arm. CR values close to 1 indicate that the line drawn between starting and target points is close to a straight line. Movement completion time is the time from the starting point to the target point at the finger marker. The CR, movement completion time, and ROM of each joint between healthy and stroke subjects were compared.

Statistical analyses were performed with the SPSS software (Statistical Packages for Social Sciences, version 17.0; SPSS Inc., Chicago, IL). Comparisons between healthy participants and stroke patients were made using independent *t*-tests. A significance level of 0.05 was used for all tests.

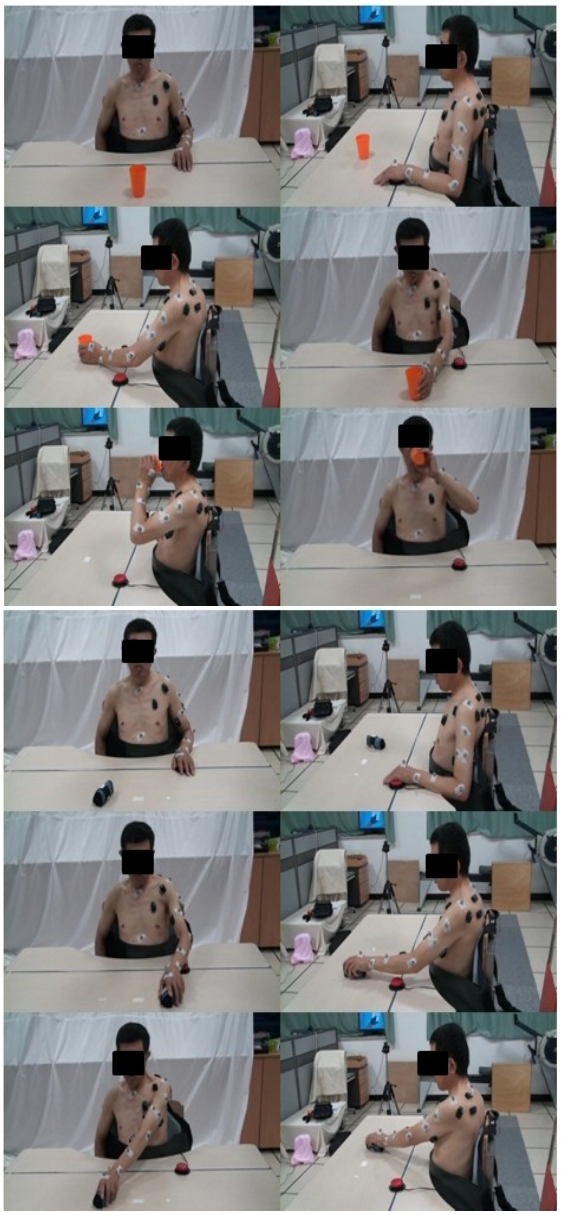

Fig. 2. Positioning of reflective markers during tasks #2-3 and #6-1.

III. RESULTS

Stroke patients showed slow curvilinear hand paths during all 12 ADL tasks. Moreover, stroke patients showed significantly smaller CR than did the healthy participants in all 12 ADL tasks (Fig. 3). We measured the mean values of completion time for each task (Fig. 4). Stroke patients significantly took almost twice as long as healthy participants to complete the movements in all tasks ($p < 0.05$). Thus, stroke patients move less efficiently than do healthy participants.

In order to investigate the angle related to the upper limb movements, we analyzed the ROM of the shoulder, elbow, and wrist joints for defined ADL tasks. The ROM of 7 movements of the 3 arm joints were analyzed: flexion–extension, abduction–adduction, and internal–external rotation motions of the shoulder joint; flexion–extension motion of the elbow joint; and radial–ulnar deviation, flexion–extension, and internal–external rotation motions of the wrist joint.

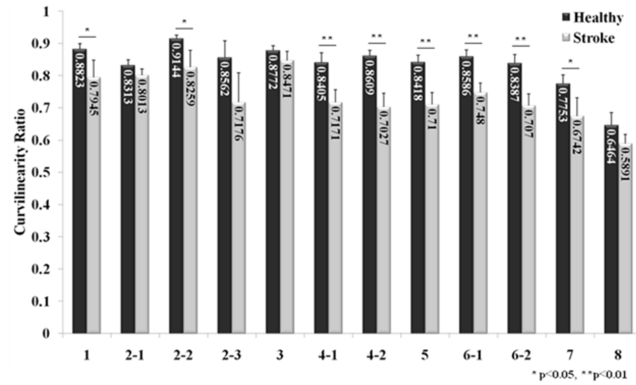

Fig. 3. Curvilinearity ratio of the 12 ADL tasks performed using an upper

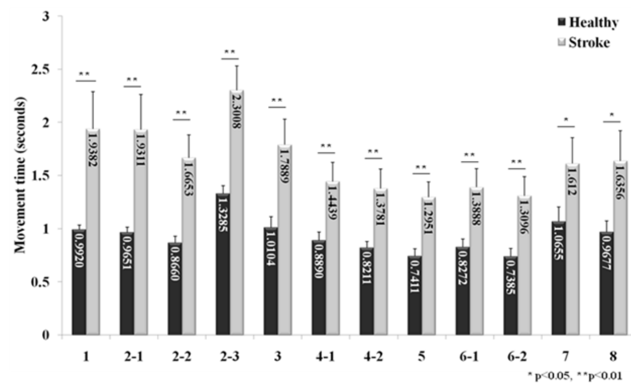

Fig. 4. Movement completion time of the 12 ADL tasks performed using an upper limb.

Fig. 5 shows the mean ROM values of healthy and stroke subjects in ADL task #2-3, which is drinking from a cup. This is the mean value of ROM of all subjects and trials. There were significant differences between healthy and stroke subjects in the abduction–adduction of the shoulder joint and flexion–extension of the elbow joint. In contrast, ROM values of stroke patients were smaller in the flexion–extension and internal–external rotation motions of the shoulder joint, but there were no significant differences.

Fig. 6 shows the mean ROM values in ADL task #3, which is reaching an ear with the arm. The ROM of stroke patients was markedly higher than that of healthy participants in the abduction–adduction and internal–external rotation motions of the shoulder joint and flexion–extension motion of the elbow joint. We found significant differences between healthy and stroke subjects in abduction–adduction and internal–external rotation motions of the shoulder joint, but not in the flexion–extension motion of the shoulder joint.

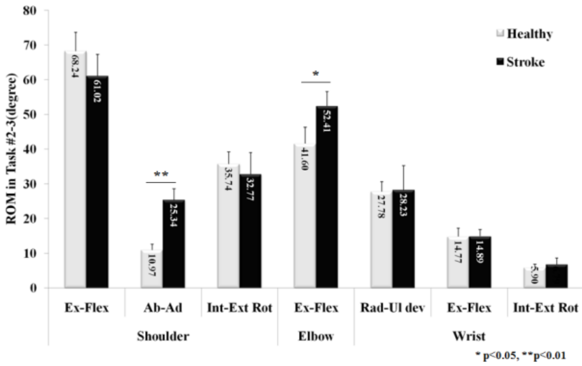

Fig. 5. Range of motion in task #2-3 (drinking from a cup).

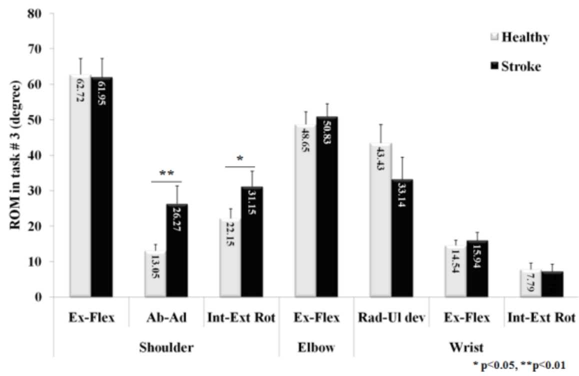

Fig. 6. Range of motion of task #3 (arm reaching side A ear).

TABLE Ⅲ
AVERAGED ROM OF HEALTH ADULTS AND STROKE PATIENTS

Joint	Shoulder Flex-Ex	Shoulder Ab-Ad	Shoulder In-Ex	Elbow Flex-Ex	Elbow Rad-Ul	Wrist Flex-Ex	Wrist In-Ex
Normal ROM	240	255	180	150	50	150	160
Task #2-3							
Healthy							
ROM	68.24	10.97	35.74	41.60	27.78	14.77	5.90
% of nROM	28.43	4.30	19.85	27.73	55.56	9.85	3.69
Stroke							
ROM	61.02	25.34	32.77	52.41	28.23	14.89	6.79
% of nROM	25.43	4.30	18.20	34.94	56.47	9.93	4.24
Task # 3							
Healthy							
ROM	62.72	13.05	22.15	48.65	43.43	15.94	7.19
% of nROM	26.13	5.12	12.31	32.43	86.85	9.69	4.87
Stroke							
ROM	61.95	26.27	31.15	50.83	33.14	15.94	7.19
% of nROM	25.81	10.30	17.31	33.89	66.27	10.63	4.50

Abbreviations: Flex-Ex = Flexion-Extension; Ab-Ad = Abduction-adduction; In-Ex = Internal-External rotation; Rad-Ul = Radial-Ulnar deviation; % of nROM = percentage of normal range of motion (unit: percentage), Unit of ROM is degree.

We analyzed the percentage of normal ROM in all the motions of the shoulder, elbow, and wrist joints in order to emphasize the ROM of each upper limb joint during functional tasks. The normal ROM represents the full ROM of a joint. The normal ROM of upper limb joints [16] is shown in Table 3. The percentage of normal range of motion (i.e., the ROM of a joint/normal ROM of a joint) was calculated. Even though the normal ROM of wrist radial–ulnar deviation motions was relatively small, the percentage of normal ROM of wrist radial–ulnar deviation motion was higher than that of other motions of the upper limb.

Fig. 7 represents the displacement of a clavicle marker in ADL task #2-3 and #3 between healthy and stroke subjects. The extent of clavicle displacement is a measure of the trunk movements of the subjects. The clavicle marker was displaced 2–3 times more in stroke patients than in healthy participants. Stroke patients adopt trunk movements as compensation strategies for the restrictions of the affected arm.

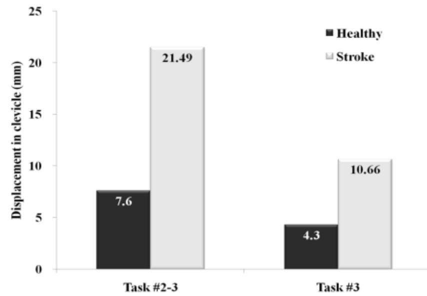

Fig. 7. Displacement of the clavicle during ADL tasks.

IV. DISCUSSION

In this paper, we defined a series of ADL tasks based on the analysis of clinical assessment tools used to evaluate the upper limb skills of stroke patients. The task definition is based on the opinion of physical medicine and rehabilitation doctors. These tasks can be used to improve functional and motor capacities by using rehabilitation robots. On the other hand, the tasks may also be applied to manual therapy in the hospital.

In the present study, motion analysis revealed that stroke patients define longer paths with their hands than do healthy participants. As a consequence, the CR values of stroke patients were lower, whereas movement completion times were longer, than those of healthy participants. Moreover, stroke patients moved their upper limbs significantly less efficiently than healthy participants. Those indices can be useful to evaluate the basic abilities of stroke patients.

Stroke patients generated increased abduction–adduction and internal–external rotation motions of the shoulder as well as flexion–extension motion of the elbow joints during ADL tasks #2-3 and #3. In accordance with a previous study [17], abnormal tone, loss of selective movement, and mass synergies characterize the ADL patterns of stroke patients. As a result, the patient's arm moves with tremendous effort and low stability during ADL tasks.

ADL tasks involve both gross movements (moving an object) and fine movements (writing). In this study, we focused on the gross movements of ADL, e.g., reaching a target and eating. We found notable differences between healthy and stroke subjects, such as an increase in abduction–adduction and internal–external motions of the shoulder joint and flexion–extension motion of the elbow joint. From the viewpoint of the ADL function, the ROM of radial–ulnar deviation motion is relatively larger than other motions in the wrist joint of both healthy and stroke subjects. In addition, the percentage of normal ROM of wrist radial–ulnar deviation motion is higher than other motions in upper limb joints during almost all ADL tasks. In that sense, rough control of wrist radial–ulnar deviation motion could be enough to perform ADL tasks using a rehabilitation robot. Based on these results, we are designing a two degree-of-freedom rehabilitation robotic arm considering the wrist radial–ulnar deviation motion and the elbow flexion–extension motion. Elbow flexion–extension motion and wrist radial–ulnar deviation motion correspond to the position and orientation of a hand, respectively. The movements of these 2 joints can be actively assisted by motors, and the movements of the other joints are passively moved. A cost-effective robot could be built because we can design a robotic arm with minimized number of motors considering the specific ADL tasks.

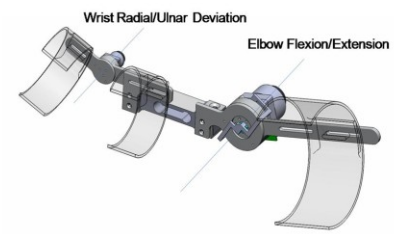

Fig. 8. Two degree-of-freedom wearable robotic arm.

Fig. 8 shows the overall concept of a wearable robotic arm. This robotic arm could be used by subacute stroke patients to train ADL tasks and exercise motions, e.g., drinking, if the robot is set with proper orientation. In addition, a simple wearable robot can be used in combination with an end-effector robot. A simple wearable robot can assist the specific joint motion, i.e., assisting or restricting, while the arm performs tasks. The robotic arm may use the control and evaluation of arm movements in stroke patients for rehabilitation therapy.

The stroke subjects that participated in this study have high motor skills, with Brunnstrom motor recovery stage 5 or 6 [8]. That means that most of them can move their hand forward. Stroke subjects in these stages have increasing voluntary and motor control, similar to healthy subjects. In that sense, the significant difference of the ROM in the upper limb joints may have occurred as compensation strategies after stroke. Actually, as compensation strategies, stroke subjects make larger trunk motions (Fig. 7). In the near future, we will examine stroke subjects at other levels of Brunnstrom motor recovery, who have strong spasticity. Those patients should actually need therapeutic rehabilitation robots. Customized training protocols can be provided to stroke patients based on the classified trajectory data, which include CR and movement completion time in accordance with stroke level. Especially, CR and movement completion time can be used to adjust the level of difficulty in the rehabilitation training quantitatively.

In summary, upper limb motions of stroke patients and healthy participants are compared during defined ADL tasks. These findings will be used as a basis to design and control cost-effective low degree-of-freedom assistive robots as well as therapeutic rehabilitation robots for upper limbs via trajectories and ROM information.

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