Master's Thesis
석사 학위논문

Validation of Fitts' Law with stroke patients' reaching task ; potential application in robot-aided upper limb rehabilitation

Jongbum Kim(김 종 범 金 鍾 範)

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Advisor : Professor Jonghyun Kim

Co-advisor : Professor Sungho Jang

By

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Robotics Engineering. The study was conducted in accordance with Code of Research Ethics[1]

7. 8. 2015

Approved by

Professor Jonghyun Kim (Signature)
(Advisor)

Professor Sungho Jang (Signature)
(Co-Advisor)

[1] Declaration of Ethical Conduct in Research**:** I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Validation of Fitts' law with stroke patients' reaching task; potential application in robot-aided upper limb rehabilitation

Jongbum Kim

Accepted in partial fulfillment of the requirements for the degree of Master of Science

5. 26. 2015

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ABSTRACT

This study deal with validation of fitts' law with stroke patients' reaching task. Fitts' Law is a linear relationship between movement time from start position to target position and Index of Difficulty (ID). ID is consisted of distance from start position to target position (A) and target width (W). Fitts' Law is a one-dimensional model of reaching movement, is commonly applied to two-dimensional reaching movement. By using fitts' law, it is possible to indicate the performance of reaching movement quantitatively. If fitts' law can be applied to stroke patients, it is easy to evaluate their reaching movement. It is possible to know intuitively by comparing between before therapy and after therapy, therefore it is comfortable method to assess stroke patients' reaching performance. It has advantage that therapy and assessment can be done at the same time by changing ID. Also, there are various possible targets in same ID in order to provide personalized therapy to patients and the interest subjects and prevent the feeling of boredom and learning effect.

Keywords: Fitts' Law, reaching task, robot-aided, rehabilitation, stroke

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Ⅰ. INTRODUCTION

1.1 Background

Recently, the American Heart Association has estimated that each year approximately 795,000 people in the USA experience a new or recurrent stroke. Of those patients, 600,000 are first attacks and 195,000 recurrent attacks [1]. Motor skills of upper limb are indispensable to interact with our daily life and navigate through our social environment. Neurological disorders such as spinal cord injuries, stroke and traumatic brain injuries frequently affect motor functions. These impairments prevent a person's participation in society, their recovery through rehabilitation therapy makes possible to re-join their social life. Therapy Intensity is important issue in rehabilitation therapy and proportional to therapy time. It means that tasks are repeated several times. Repetition therapy has some limitations. First, number of therapist is limited, it is difficult to provide same quantity of therapy. Because therapists are exhausted. Second, patients are possible to feel bore. Thereby, it is hard to recover their motor function better. In order to reduce the workload of therapist and provide effective training, robotic interventions have become more popular [2-9].

Of those motor functions, goal-direct movement consists of reaching movement and grasping movement. Reaching movement comprises several different activities : pointing – the target position is not defined precisely, yet only the direction of the distal segment of the arm; point to point without grasping – position of both the initial and target positions is known, however the orientation of hand is not relevant, neither the trajectory of the hand between the end points; point to point with grasping – complex movement that requires the orientation of the hand that corresponds to the shape of the object to be grasped, in addition to precision in getting to the target with the velocity being about the same as the object to minimize the impact; and tracking – movement along a prescribed trajectory [10]. Reaching movement is crucial in improving patient's quality of life because it is closely related to the Activities of Daily Life (ADL) and the person's participation in social life [11].

A robot, MIT-MANUS, was developed in order to provide rehabilitation therapy on reaching movement for patients [12] and is famous robot in robot-aided rehabilitation field. Of several tasks MIT-MANUS executed [13], the green clock task, which is shown in Fig.1(a) has been the most popular and representative task(Fig. 1(b))

Fig 1. (a) The green clock Task. White circle is start location and red circle is target location. Target appears clockwise from 12'o clock direction. (b) The green clock task with MIT-MANUS

Green clock task is suitable to provide repeated task, however it has two limitations. First, the user cannot practice various reaching movements required for ADL because the task just provides a reaching movement that uses a fixed moving distance as well as target size. There are problems when the target size and distance are constant. 1) It is complicated to adjust difficulty and to prevent learning effect. 2) In ADL, target size and distance contains variety of values when we perform goal-direct movement, but the green clock task does not possess those varieties. Second, the task is difficult to determine severity of patients because there are 5 parameters (Robot Initiate which explain amount of work that robot did, Distance from target, Robot power, Motion Jerk which represents smoothness level, Distance from Straight line) (Fig 2)

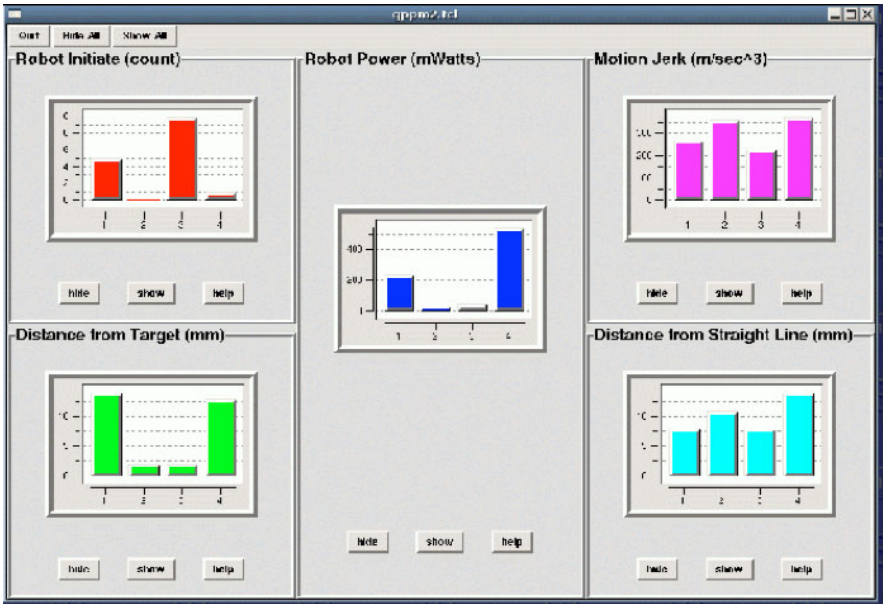

Fig 2. MIT-MANUS performance feedback matrics

1.2 Fitts' Law

Fitts' law (Equation 1) can be considered as a solution to overcome these limitations and describes a linear relationship between movement time (T) from start location to target location and the properties these locations i.e. size of the target (W) and the distance (D). The logarithmic term is called "Index of Difficulty (ID)" [14].

$$T = a + b\cdot log_2 \frac{2A}{W} \quad (1)$$

The relationship between movement time and ID can be obtained by measuring movement time for a number of difference IDs and performing a linear regression on the acquired data. This will yield values for intercept (a) and slope (b) (Fig 3) which are both distinctive for a person's or patient's current reaching motion [15]

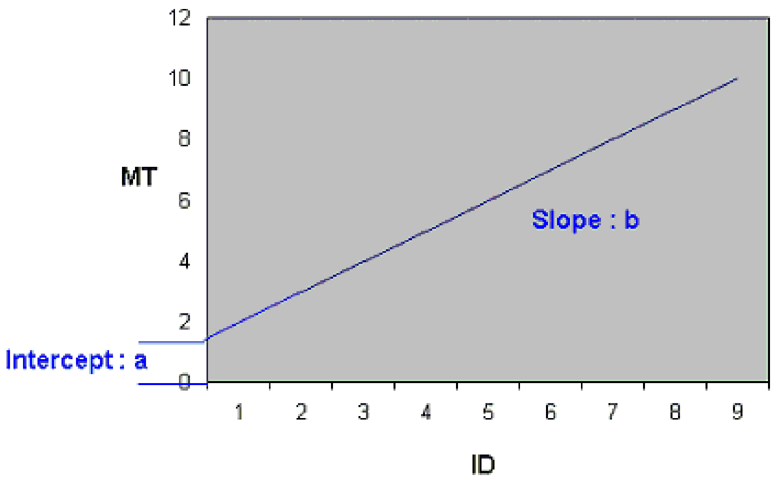

Fig 3. Linear Regression, intercept (a) and slope (b)

1.2.1 Extending Fitts' Law to two-dimensional space

Original fitts' law can be applied to 1 degree of freedom (DOF) movement [14]. Fitts' law extends to two-dimensional space and alleviates common weaknesses in applying the model [15]. Extending to two-dimensional space means that fitts' task executed with different directions. Movement direction might be planned by transforming a desired direction of movement directly into a specific pattern of coordination or synergy among different muscles [16]. A specific synergy would establish the relative intensities in different muscles appropriate for moving the hand in a given direction [17]. According to [16] and [17], movement along different direction seems to different task. However, the preceding study reported that target direction did not affect movement time [18].

1.3 Goal of the Study

Fig 3. Shows that the individual's movement time can be predicted from the target size and the distance when we know a and b. By using Fitts' law, we are expecting to obtain T of patient by the relationship above. The Fitts' law is expected to assess patients' severity easily by comparing T which is measured from experiment and another T which is calculated from ID. The preceding study applied fitts' law in order to comparison paretic side and non-paretic side of hemiplegia subjects, and they reported it was difficult to use fitts' law at paretic side [19].

People believe that time is the parameter which task part critically in adjusting the difficulty of task without robot assistive or resistive force. Also, we believe that movement time (T) can be used as a parameter which assess severity of hemiplegia patients. Fitts' law have been verified different experimental conditions with healthy subjects [15,18, 20-22]. So we think that fitt's law can be applied to our experimental environment, we hypothesize that there is no significant difference among directions based on model of fitts' Law for healthy subject and significant difference among directions based on model of fitts' law for stroke patient.

It is possible to compare the characteristic of limb based on fitts' law between healthy subjects and stroke patients. Therefore, the goal of the study is to find representative reaching movement model based on fitts' law.

Ⅱ. METHOD

2.1 Participants

10 Healthy people(male : 8, female : 2) and 4 stroke patients (male : 2, female : 2) joined our study. Our study approved by DGIST Internal Review Board (IRB). In order to understand patients' motor and cognitive function, their skills were assessed by using the upper limb part of Manual Muscle Test (MMT) [20] and the Mini-Mental State Examination (MMSE) [21]. All met following Inclusion Criteria : MMSE is higher than 24 points ; No visual and spatial deficit ; No sensory deficit ; Unilateral stroke. Exclusion Criteria : Other neurological disorders(Parkinson's Disease, Aphasia, Apraxia, Diabetes etc) ; Habitual dislocation of shoulder ; Muscular skeletal disease. Characteristics of healthy subjects and stroke patients are shown in Table 1.

Table 1. (a) List of healthy subjects that participated in the study

n	Sex	Age [y]	Dominant side (R/L)
2	F	24	2/0
8	M	26.625±1.768	7/1

Table 1. (b) List of patients that participated in the study

Patient [#]	Sex	Age [y]	On-set date	Paretic Arm	MMT		MMSE
					Shoulder Ab/Ad	Elbow Fl/Ex	
1	F	76	15.04.02	Right	4+	4+	30
2	M	37	15.03.18	Left	4	4+	30
3	M	73	15.03.28	Right	3+	4	28
4	F	32	14.11.28	Left	2-	2	26

M : male, F : female, MMT : Manual Muscle Test grade, MMSE : Mini-Mental State Examination, Ab : Abduction, Ad : Adduction, Fl : Flexion, Ex : Extension

2.2 Apparatus

2.2.1 Haptic Master

The study was performing by using a 3 degree of freedom (DOF) end-effector type robot (Haptic Master, Moog, Netherlands, Fig. 4(a)). By constraining the movement along Z-axis (Fig. 4(b)), we could compensate the gravity and implement two-dimensional planar movement at horizontal plane (Fig. 5). Because we used end-effector type robot, it is difficult to combine the arm of subjects and robot. So we used Haptic Master ADL gimbal

(Fig. 6) to unite their arm with robot easily. At the tip of the robot arm, the device includes a Force/Torque sensor that can measure position, velocity and acceleration of robot's end-effector.

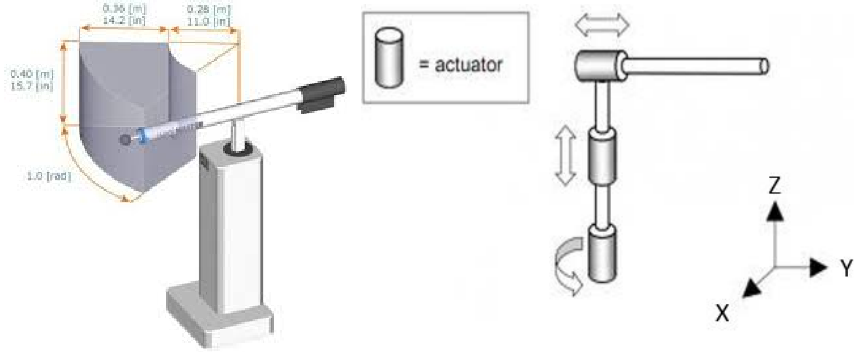

Fig 4. (a) Haptic Master (b) Haptic Master's DOF

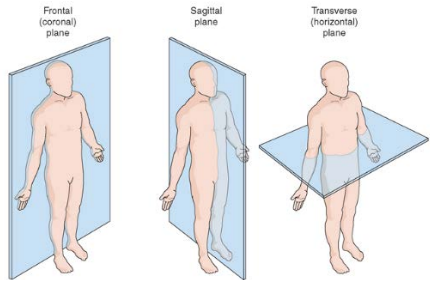

Fig 5. Body plane (Left ; Coronal plane, Center ; Sagittal plane, Right ; Horizontal plane)

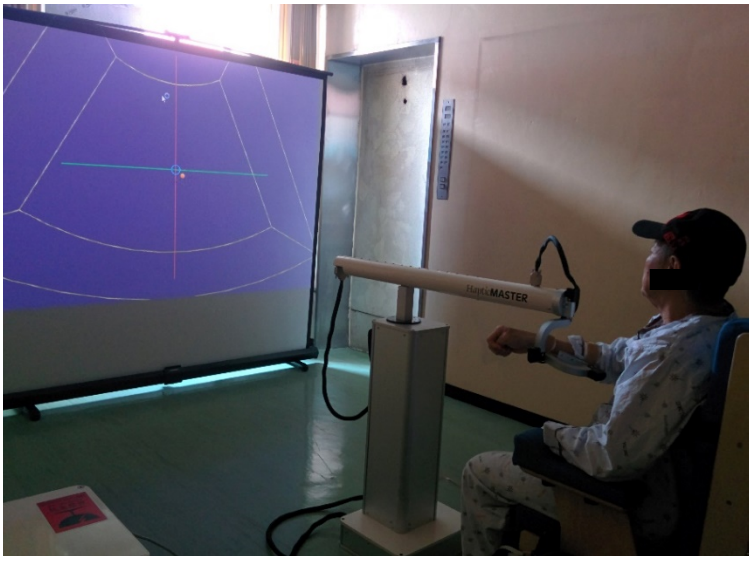

Fig 6. Unite Subject's more affected arm with Haptic Master gimbal

2.2.2 Trunk-Fixed Chair

According to the book [10], reaching movement defined as following sentence. “A complicated multi-joint movement directed to a defined point in space performed by means of coordinated rotations at the shoulder and elbow joints.” It is likely to move trunk when shoulder and elbow joints moved simultaneously. If trunk movement is included in reaching movement, it has risks to occur bad synergy and fall. Therefore in order to prevent these risks, we used the chair which can fix the trunk of participants (Fig. 7).

Fig 7. Trunk fix chair

2.3 Experimental Protocol

The study comprised four different phases (Fig. 8) : (1) Ready phase, explain to subject how to proceed experiment and combine subject’s more affected arm with gimbal of robot. (2) Exercise phase, in order to realize subject’s workspace and help to understand experiment. In case of stroke patients, we determined number of directions from workspace (Fig. 9). (3) Reaching Task phase, subject reached to target along direction with their arm. For stroke patients, they used more affected arm and for healthy subjects they used dominant arm. One session consisted of 12 trials each direction. After 1st session finish, subject took a rest for 3~5 minutes and then another sessions is progressed. Totally, 2 sessions were repeated. This protocol was repeated for 3 days, because some preceding studies used commercial mouse, joystick or touch pen [22, 25-27]. In order to adapt our device we designed repetition protocol.

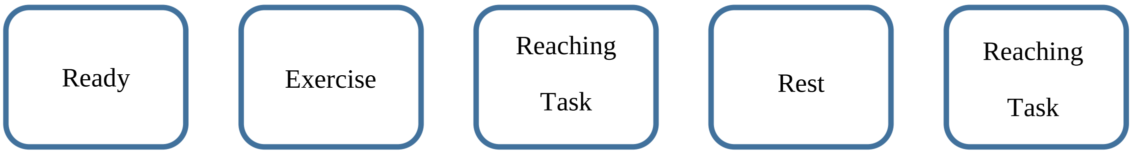

Fig 8. Experimental Protocol

Fig. 9 shows that the workspace of stroke patient (subject 2). Red circle used to determine that the directions will be used in experiment or not. Clockwise from the 6'0 clock direction, it was defined from 1st direction to 8th direction. As the result is shown in Table 2.

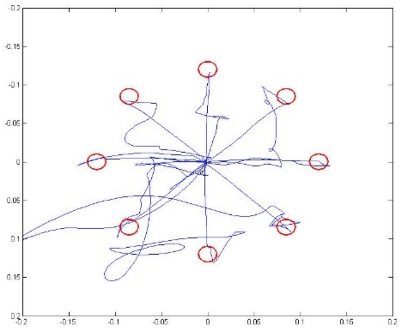

Fig 9. Subject 2's workspace

Table 2. Used number of direction

Patient [#]	Used number of direction
1	4
2	8
3	7
4	8

2.4 Data Analysis

Experiments were executed by using a commercial Lab-top. All statistical analyses were generated using IBM SPSS. Parameters were compared using a one-way ANOVA. Post hoc analyses were performed using a Tukey HSD. The significance level was set to $p < 0.05$.

Ⅲ. RESULT

3.1 Healthy Subjects

3.1.1 Validation of Fitts' Law

In order to verify fitts' law is valid or not, we determined the slopes, intercepts and correlation coefficients through linear curve fitting (Table 3).

Table 3. Result of linear curve fitting

	All sessions			1st session			2nd session		
	a	b	r^2	a	b	r^2	a	b	r^2
Subject 1	1091.5	253.97	0.643	1069	243.91	0.657	1110.8	265.59	0.6824
Subject 2	1055.6	228.89	0.6296	1072.3	232.78	0.6184	1038.9	224.99	0.663
Subject 3	807.72	369.06	0.8344	803.77	358.93	0.8321	811.66	379.16	0.8507
Subject 4	967.68	207.63	0.6342	978.57	205.48	0.5955	956.82	209.75	0.6781
Subject 5	991.5	292.09	0.671	942.08	323.99	0.7043	1040.9	260.19	0.6537
Subject 6	1118.8	220.3	0.6584	1118.8	222.78	0.6735	1112.1	227.73	0.6604
Subject 7	940.21	360.23	0.6628	859.06	377.13	0.7216	1021.4	343.33	0.6298
Subject 8	1006.1	302.99	0.6034	1013.5	312.02	0.6267	997.59	294.36	0.5923
Subject 9	1065.6	266.52	0.3935	1090.4	179.53	0.5401	1029	342.72	0.5517
Subject 10	1247	299.47	0.513	1210.2	282.53	0.5699	1283.8	316.4	0.5311

It seems that fitts' law is not applicable to healthy subjects (except Subject 3). Because Index of Diffculty (ID) is consisted of two variables (A; distance from start position to target position, W; target width), in order to clarify which variable influence r^2, we analyzed the data through one variable is fixed. First, we fixed target width (W). In Table 3, only subject 3's data showed that fitts' law is available, however, when target width is 0.01m, fitts' law is not applicable. Moreover, if we excluded W=0.01m data, 7 of 10 subjects satisfied fitts' law (Table 4). It might mean that there is valid range of target width despite of healthy subject.

Table 4. Analyzed the data W is fixed

	W = 0.01m			W = 0.02m			W = 0.03m		
Subject #	a	b	r^2	a	b	r^2	a	b	r^2
S1	21.25	581.9	0.64	578.2	507.4	0.73	789.3	485.2	0.81
S2	398.5	428.3	0.49	548	482.9	0.74	823.8	402.2	0.7
S3	-76.1	651.9	0.637	614	449.8	0.74	811.3	391.4	0.824
S4	10.953	515.62	0.548	703.2	334.75	0.74	878.5	288.5	0.782
S5	121.83	642.22	0.5161	655	457.9	0.72	872.42	394.2	0.83
S6	119.25	528.11	0.793	606	475.8	0.8586	825.1	440.7	0.837
S7	-454.6	793.9	0.651	381.9	634.4	0.628	692.7	558.3	0.632
S8	-158.4	666.2	0.553	497.2	545.7	0.662	696.7	547.1	0.638
S9	178.6	536.4	0.24	415.7	593.5	0.463	852.1	426.8	0.448
S10	-99.15	709.3	0.608	438.5	701.6	0.7	587.34	785.1	0.78

Second, we fixed distance from start position to target position (A). Table 4 shows that if we excluded the data when W=0.01m, fitts' law is applicable, however, Table 5 does not show tendency. Generally, when A is changed (W is fixed), movement time increased linearly with Index of Difficulty (ID).

Table 5. Analyzed the data when A is fixed

	A = 0.072m			A = 0.088m			A = 0.104m			A = 0.12m		
	a	b	r^2	a	b	r^2	a	b	r^2	a	b	r^2
S1	1159	159.1	0.668	1168.5	188.9	0.68	1303.6	169.8	0.509	1292.2	228.2	0.582
S2	1066	187.4	0.7	1125.8	168.9	0.683	1176	178.9	0.486	1262.3	194.5	0.551
S3	946	263.7	0.855	867.1	334.6	0.849	804.7	370.1	0.839	791.8	399.8	0.785
S4	1049.1	128.9	0.747	1086	133.7	0.669	1109.9	147.7	0.471	909.6	265.5	0.675
S5	1114.2	183.3	0.729	1097	218.8	0.758	1063.6	268.2	0.659	1035.6	314.8	0.557
S6	1146.9	146	0.832	1231.3	146.2	0.766	1258.9	171.5	0.716	1364.1	174.5	0.678
S7	1048	236.7	0.737	1090	257.1	0.6	1035	339.2	0.616	1126.1	338.3	0.572
S8	1097	191.9	0.573	238.9	1088	0.61	1076	284.5	0.533	1285	246.5	0.495
S9	1115.5	192	0.374	1155.7	193.7	0.348	1125.3	249.7	0.284	1325.6	214.4	0.217
S10	1199.1	229.4	0.715	1417.3	182.9	0.474	1493.2	222.5	0.47	1745.2	178.1	0.253

3.1.2 Difference among directions

All subjects did not show significant difference among directions. Table 6 shows that the result of statistical analysis.

Table 6. Significance level of healthy subjects

	p-value
S1	0.165
S2	0.371
S3	0.341
S4	0.550
S5	0.727
S6	0.6
S7	0.207
S8	0.707
S9	0.549
S10	0.31

*p<0.05

Our purpose of study with healthy subjects is to find representative reaching movement model based on fitts' law. In order to investigate that we can find the model or not, we analyzed the difference at the same direction between sessions. All subjects did not show significant difference between sessions. Fig 10 shows an example. Box and error bar indicate average of movement time and standard deviation of movement time respectively.

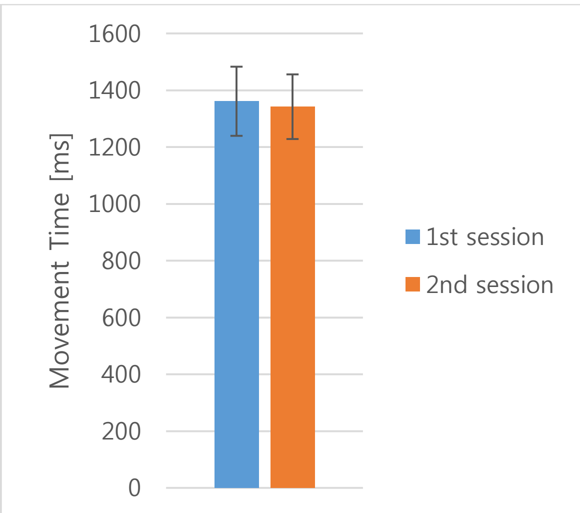

Fig 10. Compare the movement time between sessions

3.2 Stroke patients

3.2.1 Change of r^2 as experiment was repeated

To illustrate the values that were used for the estimation of the time needed for the movements during experiments, Table 3 shows the slopes, intercepts and correlation coefficients. When Correlation of the data is at r^2>0.7, correlation is good [19]. As experiment were repeated, r^2 increased for S3. For S1, 3rd day's r^2 is the highest, for S2, 2nd day's result scored the highest r^2. MMT score of more affected side of S4 is quite low, slope did not decrease as experiment was repeated (Table 7. (d)).

Table 7. (a) Result of linear regression for subject 1

Day 1	a	b	r^2
All sessions	-2809.9	3516.9	0.2576
1st session	-5464.6	5213.9	0.3419
2nd session	254.04	1570.8	0.3777
Day 2			
All sessions	1060.6	1147.3	0.208
1st session	373.7	1418.2	0.2718
2nd session	1774.2	861.35	0.144
Day 3			
All sessions	177.53	1236.3	0.3753
1st session	47.225	1324.8	0.3427
2nd session	262.3	1169.1	0.4234

Table 7. (b) Result of linear regression for subject 2

Day 1	a	b	r^2
All sessions	404.66	992.55	0.338
1st session	298.47	1044.4	0.3492
2nd session	510.85	940.65	0.3271
Day 2			

All sessions	441.9	856.92	0.4663
1st session	448.85	853.35	0.4388
2nd session	434.93	860.52	0.497
Day 3			
All sessions	680.39	733.8	0.3553
1st session	680.35	693.23	0.3873
2nd session	668.11	781.83	0.3432

Table 7. (c) Result of linear regression for subject 3

Day 1	a	b	r^2
All sessions	533.9	942.18	0.2737
1st session	588.83	925.93	0.2346
2nd session	478.52	961.75	0.4057
Day 2			
All sessions	951.11	309.06	0.3443
1st session	1222.2	-167.29	0.3853
2nd session	689.76	759.44	0.3437
Day 3			
All sessions	515.92	861.52	0.4278
1st session	595.73	649.11	0.4679
2nd session	448.64	1042.1	0.4001

Table 7. (d) Result of linear regression for subject 4

Day 1	a	b	r^2
All sessions	216.43	2630.1	0.166
1st session	451.72	2540.4	0.174
2nd session	-20.367	2720.8	0.1599
Day 2			

All sessions	250.44	2538.7	0.1722
1st session	-734.23	2693.4	0.3294
2nd session	122.8	2394.9	0.1114
Day 3			
All sessions	15.424	2378.7	0.1698
1st session	3030.4	901.64	0.0425
2nd session	-2933.6	3797.5	0.3072

Moreover, which variable of target components (A, W) was influenced r^2, we analyzed the result through one variable is fixed. First, we fixed W (Table 8). Intercept and slope were not steady, r^2 is very low. As experiment was repeated, r^2 did not increase. Day 2's result recorded the highest r^2 among experiment days.

Table. 8 (a) Analyzed the result when W is fixed (Day 1)

	W = 0.01m			W = 0.02m			W = 0.03m		
Subject #	a	b	r^2	a	b	r^2	a	b	r^2
S1	-29226	12127	0.274	-3259	3280	0.146	512.1	1978.1	0.063
S2	-1948	1751.1	0.137	0.126	1152.4	0.135	655.8	887.6	0.196
S3	-786.7	1093.6	0.152	620.9	664.3	0.117	1323.4	318.8	0.047
S4	9366.3	-301	0	686.3	2449.2	0.029	-176.4	2728.3	0.103

Table. 8 (b) Analyzed the result when W is fixed (Day 2)

	W = 0.01m			W = 0.02m			W = 0.03m		
Subject #	a	b	r^2	a	b	r^2	a	b	r^2

S1	-5797	3259.7	0.232	-1668	2623.1	0.216	-146	1990.7	0.268
S2	-1500	1492	0.172	297.2	882	0.286	966.7	557.1	0.268
S3	-3220	2099.1	0.185	-243.5	1114	0.386	456.2	998.3	0.173
S4	6951.3	504.4	0	948.4	1899	0.03	2324.7	1245.4	0.01

Table 8. (c) Analyzed the result when W is fixed (Day 3)

	W = 0.01m			W = 0.02m			W = 0.03m		
Subject #	a	b	r^2	a	b	r^2	a	b	r^2
S1	-317.6	1387.4	0.064	-553.2	1658.4	0.142	254.35	1252.5	0.326
S2	-954.4	1271.8	0.135	366.8	834.1	0.202	1029.3	566.9	0.116
S3	-351.6	910.6	0.204	341.9	727.1	0.393	943.9	518.7	0.165
S4	4264.5	1079.3	0.004	3885.1	494.4	0.003	1218.5	1414.6	0.033

Second, we fixed A. Generally, r^2 is higher than the result which W is fixed, r^2 is still low.

Table 9. (a) Analyzed the result when A is fixed (Day 1)

	A = 0.072m			A = 0.088m			A = 0.104m			A = 0.12m		
	a	b	r^2	a	b	r^2	a	b	r^2	a	b	r^2
S1	1851	805.2	0.047	26.263	1610	0.24	-2534	3211	0.177	-8930	6684.1	0.396
S2	592.3	938.9	0.251	967.4	614.7	0.204	865.4	677	0.31	-482.9	1498	0.425

S3	1347	275.7	0.14	998.5	511.4	0.263	980	473.8	0.357	566.2	734	0.22
S4	-757	3514.2	0.277	-1504	3389.4	0.277	-123	2681.9	0.112	1982.4	1851.3	0.067

Table. 9 (b) Analyzed the result when A is fixed (Day 2)

	A = 0.072m			A = 0.088m			A = 0.104m			A = 0.12m		
	a	b	r^2	a	b	r^2	a	b	r^2	a	b	r^2
S1	1327	871.8	0.286	2298.7	289	0.04	1618.7	771.1	0.086	457.8	1908	0.311
S2	832.8	643.7	0.322	813.3	612.2	0.46	168.3	997.6	0.355	4239	-593.9	0.205
S3	778.7	645.3	0.421	638.4	709.4	0.289	826.4	687.3	0.32	-393.7	1359.7	0.278
S4	-502	3122.7	0.339	907.3	2473.2	0.147	-1954	3474.3	0.167	200.8	2234.1	0.133

Table 9. (c) Analyzed the result when A is fixed (Day 3)

	A = 0.072m			A = 0.088m			A = 0.104m			A = 0.12m		
	a	b	r^2	a	b	r^2	a	b	r^2	a	b	r^2
S1	114.1	1365.1	0.408	405.2	1075	0.194	1748.9	518.7	0.157	856.7	1810.3	0.532
S2	981.8	531.4	0.244	920.8	606.9	0.291	611.7	775.8	0.217	343.1	889.6	0.541
S3	1069.1	409.9	0.355	948.9	401.8	0.58	940.2	450.6	0.434	790.3	624.9	0.32
S4	-119	2953.1	0.228	-667	2704	0.289	448.9	1799.6	0.133	-2220	3255	0.147

3.2.2 Change of r^2 along direction

We hypothesize that there is significant difference along direction for stroke patients. We decided to use number of direction according to subject's workspace (See Table. 2). There is difference among patients' workspace, so used number of direction is different. Table 8 shows that the slopes, intercepts and correlation coefficients each direction. Generally, fitts' law cannot be applied to stroke patient's more affected arm. However, fitts' law is available partially (subject 1 : Day 1 of 3rd direction of 2nd session, subject 2 : Day 2 and Day 3 of 3rd direction of 1st session, subject 3 : Day 2 and Day 3 of 4th direction of 1st session).

Table 10. (a) The slopes, intercepts and correlation coefficients each direction for subject 1

Day 1	All sessions			1st session			2nd session		
	a	b	r^2	a	b	r^2	a	b	r^2
D1	-696	2034	0.16	-4534	3735	0.29	3142	332	0.03
D2	-1423	2461	0.25	-2036	2928	0.22	-722	1961	0.66
D3	-6416	6243	0.43	-9923	9177	0.64	-3160	3298	0.85
D7	-2434	3248	0.32	-5342	5016	0.52	2341	297	0.05
Day 2									
D1	753	1072	0.22	-414	1715	0.37	2485	114	0.01
D2	1866	558	0.13	559	1021	0.49	3317	-2.1	0
D3	644	1750	0.31	-1178	2341	0.41	2466	1158	0.24
D7	1335	1011	0.23	2883	381	0.03	11.7	1516	0.49
Day 3									
D1	1342	768	0.7	1167	885	0.32	1122	815	0.34
D2	-83	1222	0.47	-224	1296	0.46	58.2	1150	0.49
D3	-813	1731	0.56	-1154	1978	0.54	-490	1494	0.65
D7	1070	993	0.17	573	1035	0.20	1692	881	0.15

D1 : 1st direction, D2 : 2nd direction, D3 : 3rd direction, D7 : 7th direction

Table 10. (b) The slopes, intercepts and correlation coefficients each direction for subject 2

Day 1	All sessions			1st session			2nd session		
	a	b	r^2	a	b	r^2	a	b	r^2
D1	1239	708.19	0.301	2018	584	0.263	460.85	831.89	0.6572
D2	325.6	939.83	0.661	-142.6	1061	0.715	793.78	818.27	0.7069
D3	-446.2	1285.3	0.408	-898.8	1483.4	0.395	6.4118	1087.3	0.467
D4	636.99	619.75	0.431	826.16	475.69	0.503	447.82	763.82	0.4599
D5	254.96	1297.3	0.387	17.336	1716.5	0.636	492.59	878.04	0.3432
D6	243.32	1013.2	0.434	365.08	870.54	0.471	121.55	1155.8	0.4477
D7	1493.1	486.97	0.208	542.33	864.93	0.699	2443.9	109.02	0.0103
D8	-509.9	1589.8	0.439	-339.8	1298.6	0.497	-680.1	1881	0.4876
Day 2									
D1	737	852.3	0.474	313.6	1147	0.546	1186	531.4	0.73
D2	-30.1	1173	0.517	657.8	863.8	0.817	-718	1483.4	0.498
D3	259.8	788	0.691	69.85	884.26	0.809	450	691.9	0.579
D4	555.6	597	0.638	464.6	628.81	0.68	647	559	0.596
D5	1277	451	0.298	1641	163.1	0.196	913	738	0.576
D6	319	912	0.696	7.96	1099	0.695	630.6	725.7	0.857
D7	793.2	736	0.472	1113.1	516.65	0.351	473.5	955.2	0.638
D8	386	1358	0.638	-680	1524.4	0.573	-94.63	1192	0.832
Day 3									
D1	1288	367.5	0.257	2220	-75.5	0.033	364.6	808.2	0.75
D2	793.1	799	0.433	423.3	913.9	0.513	1158	687.6	0.369
D3	24.8	927	0.678	-430	1135	0.8032	479.7	718	0.556
D4	173.9	852	0.602	-90.6	979.7	0.659	438.5	724.9	0.549

D5	1721	124.5	0.02	993.1	303.2	0.253	2390	-21.7	0
D6	946.2	607.7	0.41	1054.7	560	0.608	837.8	655.3	0.335
D7	100.6	1181	0.387	1066.2	665.4	0.265	982.2	1777	0.537
D8	581.6	922.4	0.618	277.73	1015.6	0.734	885.5	829.2	0.525

Table 10. (c) The slopes, intercepts and correlation coefficients each direction for subject 3

Day 1	All sessions			1st session			2nd session		
	a	b	r^2	a	b	r^2	a	b	r^2
D2	196.28	857.05	0.4342	-7.021	1078	0.4576	399.57	636.12	0.759
D3	1223.6	310.45	0.4125	1202.6	317.76	0.3408	1244.6	303.13	0.5377
D4	1382.2	476.5	0.3212	1329.9	575.34	0.3313	1447.3	378.26	0.4431
D5	1413.3	153.81	0.0853	1898.4	-60.28	0.0167	928.1	367.89	0.403
D6	1328.4	379.85	0.1846	1735.7	67.575	0.0162	921.17	692.13	0.4905
D7	667.5	735.25	0.405	307.11	1050.9	0.5683	1027.9	419.6	0.6035
D8	437.28	815.35	0.4088	43.066	1093.9	0.4718	831.49	536.85	0.5442
Day 2									
D2	212.5	844.9	0.5418	-240.5	1067.6	0.5501	665.51	622.31	0.6946
D3	-135.8	1311.5	0.3178	1292.9	2021.1	0.4309	1021.4	601.97	0.5184
D4	-566.4	1522.5	0.6878	-1199	1970.4	0.8142	66.472	1074.6	0.7778
D5	1117.8	478.17	0.2501	858.84	600.89	0.4881	1376.8	355.45	0.1161
D6	917.13	614.67	0.4184	521.51	823.15	0.5005	1312.7	460.19	0.3447
D7	818.34	614.09	0.4889	1248	486.44	0.364	388.7	741.74	0.6795
D8	-200.2	1244.8	0.3347	-922.2	1513.6	0.4521	521.84	958.01	0.2771
Day 3									
D2	693.41	576.8	0.4689	143.53	812.84	0.5309	1245	340.95	0.6778

D3	884.47	520.46	0.7137	774.07	564.22	0.7704	994.86	476.69	0.6584
D4	710.67	646.06	0.8068	772.54	592.36	0.7841	642.19	701.87	0.8512
D5	754.97	500.83	0.456	396.2	714.56	0.5484	1021.9	341.16	0.5142
D6	850.58	497.3	0.2885	431.96	667.91	0.3171	1318.2	297.85	0.4621
D7	1293.9	345.34	0.2534	1079.2	382.23	0.4193	1508.6	308.45	0.1812
D8	839.1	450.79	0.499	1026.7	393.23	0.3789	782.87	495.32	0.5973

Table 10. (d) The slopes, intercepts and correlation coefficients each direction for subject 4

Day 1	All sessions			1^{st} session			2^{nd} session		
	a	b	r^2	a	b	r^2	a	b	r^2
D1	-833.2	2074	0.3433	-1308	2515	0.3634	-360.9	1655.7	0.3988
D2	580.75	1197.9	0.312	287.73	1400.5	0.2896	873.78	995.29	0.4245
D3	3928.5	390.54	0.012	7808	-829	0.0494	48.893	1610.1	0.416
D4	-1474	4219	0.2451	-2973	5751.3	0.2958	259.86	2632.5	0.342
D5	2036.1	1847.7	0.1707	4140.8	1271.4	0.0792	-68.5	2477.9	0.3321
D6	-4.638	3668.4	0.2641	-3618	4564.8	0.5452	2771.9	3608.3	0.1436
D7	-1352	4331.4	0.2631	894.63	2517.1	0.5896	-3599	6145.6	0.3148
D8	-1378	3396.2	0.3209	-1789	3172	0.3542	-995.4	3597.2	0.3167
Day 2									
D1	67.251	1493.9	0.4	490.07	1359.7	0.3732	-358.6	1628	0.4328
D2	1999.8	1032.8	0.08	724.9	1440.3	0.33	3274.6	625.24	0.02
D3	2217.7	957.84	0.194	1463.7	1607	0.39	-773.9	2954	0.359
D4	-1907	3611	0.4376	-2915	4185	0.51	-774	2954.8	0.36
D5	1710	1430	0.18	624	2006	0.21	2797	839.2	0.23
D6	2883	2574.8	0.21	1255	3981	0.526	7021.5	1168.5	0.047
D7	3896.2	2288.1	0.136	1407.7	2226.7	0.3426	6384.7	2349.5	0.1524

D8	10920	7643.5	0.4756	-7785	5139.8	0.699	-13803	10052	0.5864
Day 3									
D1	-710.1	1989.1	0.3431	1066.5	1181.1	0.3613	-2486	2797	0.41
D2	980.9	834.5	0.34	1234	629.5	0.28	738.6	1036	0.415
D3	-1586	2635.3	0.3284	2453.7	461.8	0.039	-5631	4860.6	0.689
D4	-924.9	3078	0.212	5995.7	-79.18	0.004	-8323	6383.2	0.558
D5	1388.1	1759.6	0.1049	4166.2	276.5	0.008	-1390	3242.8	0.217
D6	789.7	3861	0.24	7856.3	911.3	0.068	-6280	6810.6	0.42
D7	289	3134.4	0.3487	-1661	4132.8	0.5426	1440.1	2633.4	0.248
D8	-1103	2386.9	0.4479	-578.5	2067.2	0.3443	-1627	2706.6	0.5679

3.2.3 Change of Movement time along direction

Comparing the values (slopes, intercepts), it seems to be difference among directions. We want to know that there is significant difference among directions or not by using one-way ANOVA. Because r^2 is smaller than 0.7, it is hard to believe intercept (a) and slope (b) are valid. Therefore, we used movement time to analyze significant level. Table. 11 and Fig. 11 show that the result of one-way ANOVA and host-poc analysis, respectively. * indicated that p<0.05. Box and error bar mean that average and standard deviation of movement time, respectively.

Table 11. Significance level of stroke patients according to days

	Day 1	Day 2	Day 3
S1	0.003*	0.001*	0.058
S2	0.001*	0.044*	0.006*
S3	0.006*	0.009*	0.992
S4	0.000*	0.000*	0.042*

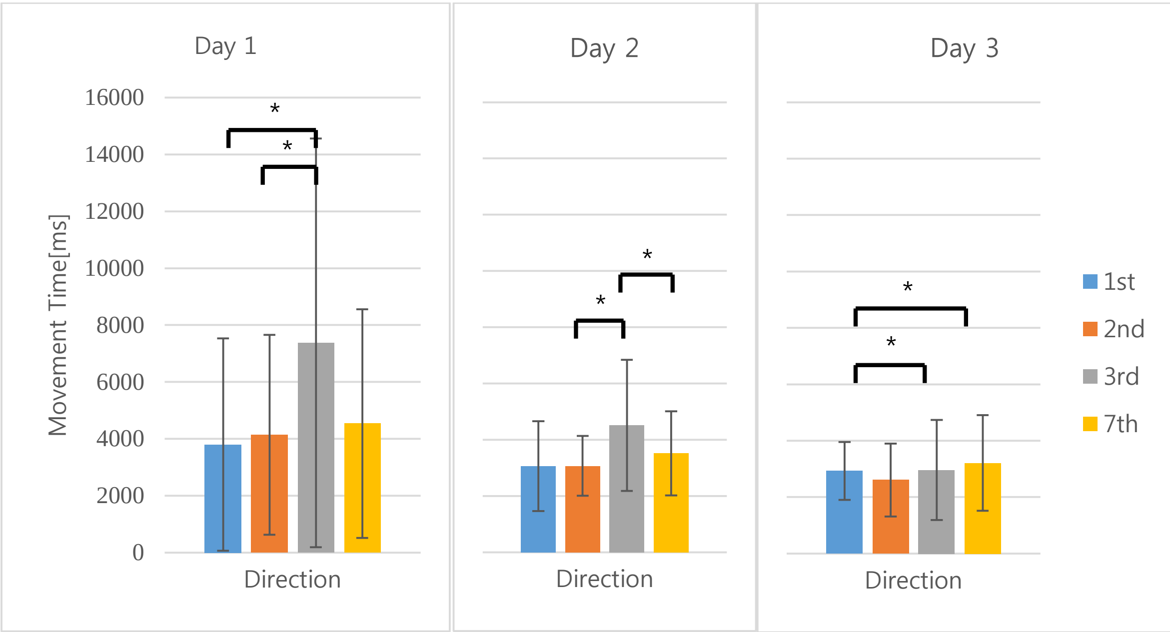

Fig. 11 (a) Comparing movement time among directions and days for subject 1

In case of subject 1, as experiment was repeated, the direction which indicated significant difference is different. Average and standard deviation of movement time decrease as experiment is repeated. As a result, p-value increased.

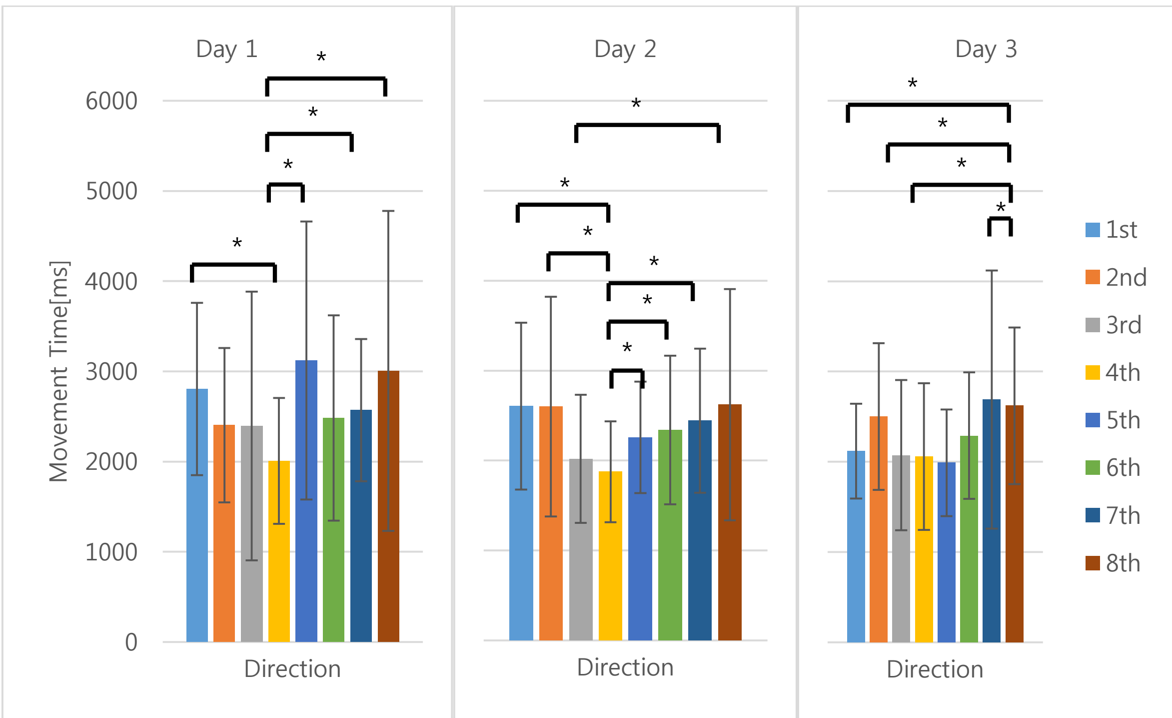

Fig. 11 (b) Comparing movement time among directions and days for subject 2

In case of 3rd day of subject 2, there is significant difference between 7th direction and all other directions.

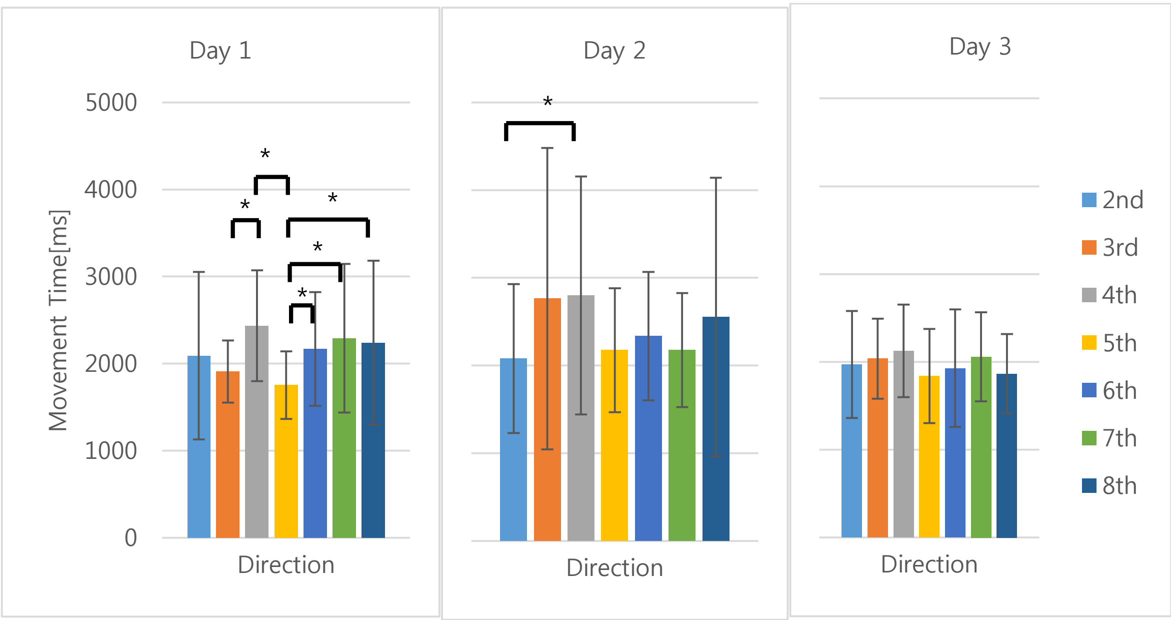

Fig. 11 (c) Comparing movement time among directions and days for subject 3

As experiment was repeated, significant difference disappeared, furthermore average and standard deviation of movement time was decreased.

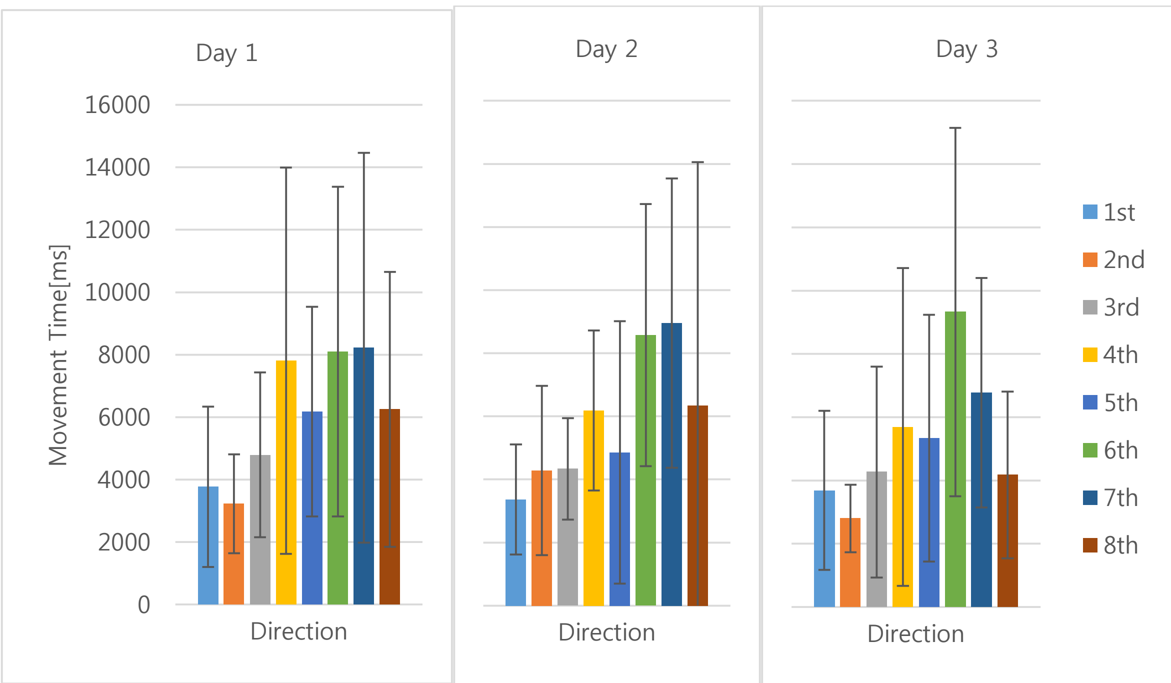

Fig. 11 (d) Comparing movement time among directions and days for subject 4

More affected side's motor function is quite low, there are many combinations which indicate significant difference among directions. It means that there is significant difference of performance among directions. Table 12 shows that combination of directions which indicate significant difference among directions.

Table 12. Combination of directions which indicate significant difference (Subject 4)

Day 1		Day 2		Day 3	
1st direction	2nd, 3rd, 4th, 6th, 7th, 8th	1st direction	4th, 6th, 7th	1st direction	4th, 5th, 6th
2nd direction	3rd, 4th, 5th, 6th, 7th, 8th	2nd direction	6th, 7th	2nd direction	3rd, 4th, 5th, 6th, 7th, 8th
3rd direction	4th, 6th, 7th, 8th	3rd direction	4th, 5th, 6th, 7th, 8th	3rd direction	6th
4th direction	5th	4th direction	5th, 8th	4th direction	8th
		5th direction	6th, 7th, 8th	6th direction	7th, 8th

Ⅳ. DISCUSSION

4.1 Healthy Subjects

All subjects did not show significant difference among directions. In order to find representative reaching movement model based on fitts' law, we compared the data of same direction. Fig 10 shows that there is no significant difference between sessions.

When we excluded W=0.01 data, Fitts' law is applicable to 7 of 10 subjects. The data did not show significant difference among directions as well as sessions. It is possible to find representative reaching movement model based on fitts' law. However, we can find the model when W=0.01 data was excluded, it means that it is hard to apply fitts' law with all range of W under these experimental environment.

Under our experimental condition, we used gimbal in order to combine subject's limb and robot. Reaching movement was performed by their forearm not but their hand. However, hand-eye coordination is crucial component in reaching movement. Therefore, we changed end-effector from gimbal to hand handle type. As a result, subjects who did not satisfy fitts' law satisfied. (Fig. 12)

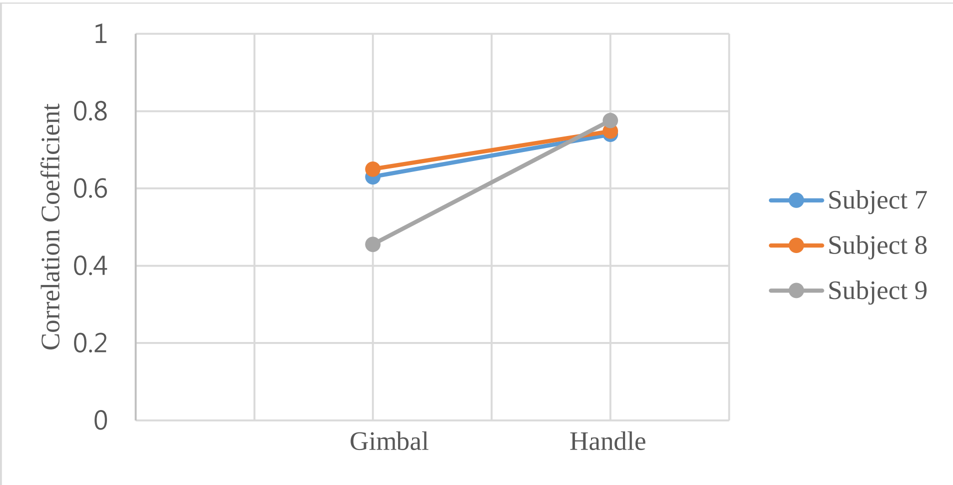

Fig. 12 Change of r^2

4.2 Stroke Patients

There is significant difference among directions for all subjects, of those subjects, subject 4 who scored the worst MMT scale had lots of combinations which indicated significant difference among directions.

Furthermore, average and standard deviation of movement time of are larger than other subject's average and standard deviation of movement time. Fig. 13 shows that the recorded path of each subject. As you see in Fig. 12, Subject 4's path shows many indirect path.

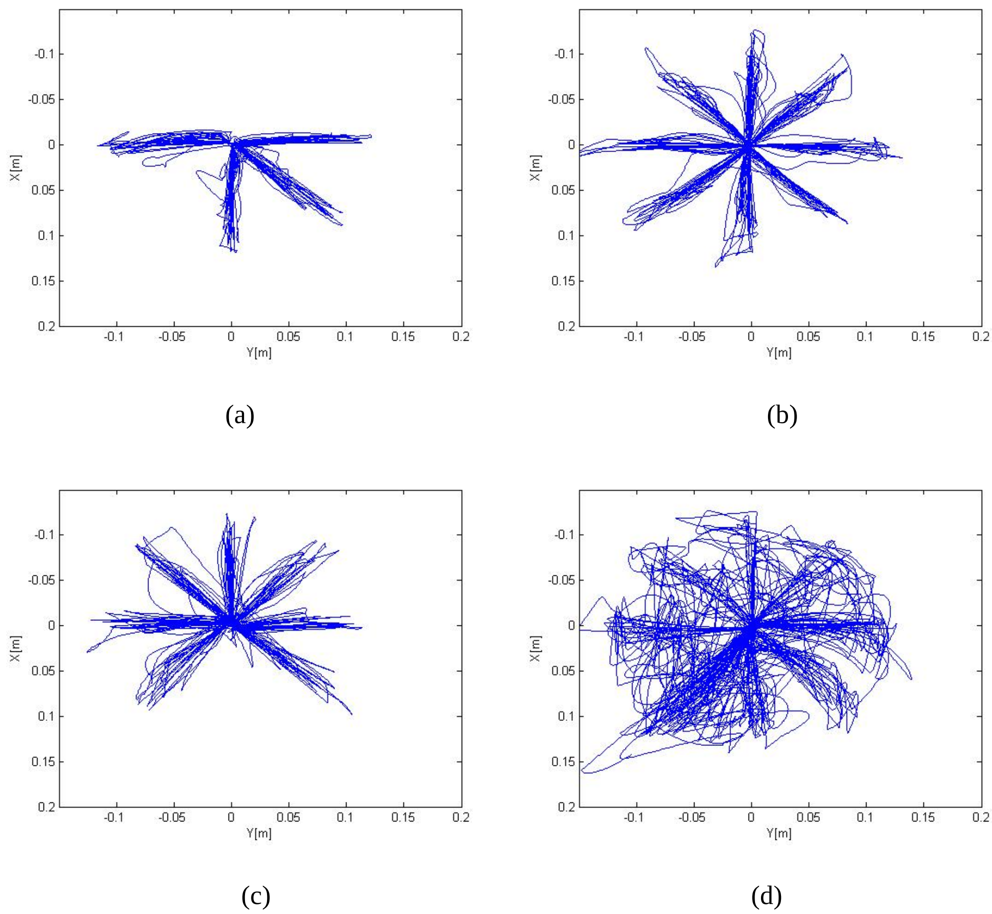

Fig. 13 The recorded path of each subject ((a) : S1, (b) : S2, (c) : S3, (d) : S4)

It is hard to compare the performance among experiment days by using fitts' law, so we compared the velocity profiles among experiment days. As experiment was repeated, Average of movement time tends to decrease. It means that velocity profile is changed. Change of velocity profile occurs the change of movement time, as a result, fitts' slope (b) is decreased.

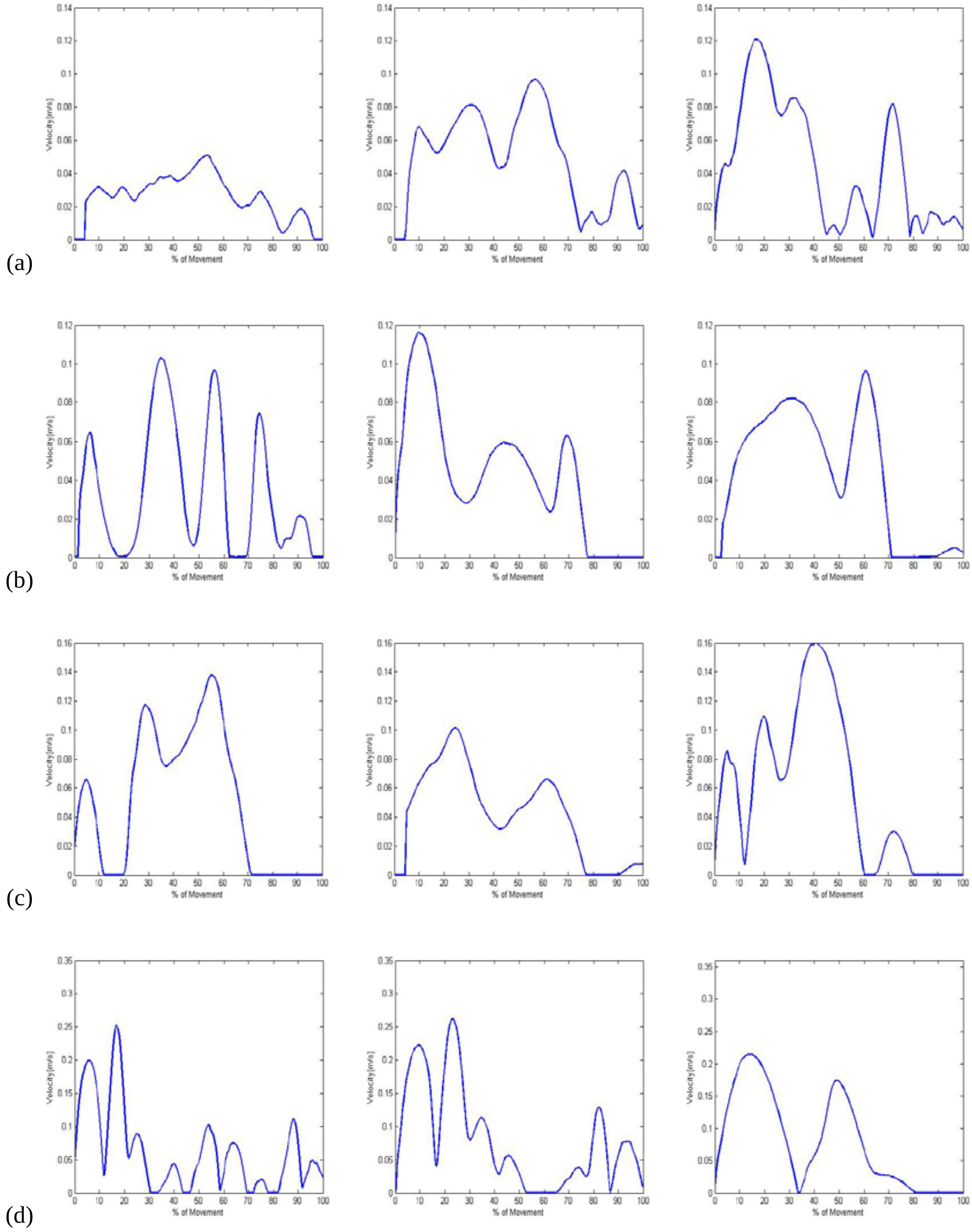

Fig. 14 Comparison velocity profile among experimental dates

(First Column: Day 1, Second Column: Day 2, Third Column: Day 3, (a): S1, (b): S2, (c): S3, (d): S4)

Except subject 4, other subjects' velocity profile became larger. As velocity profile became larger, movement time decreased. Furthermore, there is a direction which fitts' law is applicable (Table. 13). This case existed partially, so it will be necessary to study the method how to use this partial data in order to apply fitts' law to stroke patients.

Table. 13 (a) Subject 1's 3rd direction result

	All sessions			1st session			2nd session		
	a	b	r^2	a	b	r^2	a	b	r^2
Day 1	-6416	6243	0.431	-9923	9177	0.636	-3160	3298	0.846
Day 2	643.6	1750	0.309	-1178	2341	0.413	2466	1158	0.242
Day 3	-813	1731	0.557	-1153	1978	0.54	-491	1494	0.652

Table. 13 (b) Subject 2's 3rd direction result

	All sessions			1st session			2nd session		
	a	b	r^2	a	b	r^2	a	b	r^2
Day 1	-446	1285	0.408	-899	1483	0.395	6.412	1087	0.467
Day 2	259.8	788	0.692	69.85	884.3	0.81	450	692	0.579
Day 3	24.8	926.8	0.678	-430	1136	0.803	479.7	718	0.556

Table. 13 (c) Subject 3's 4th direction result

	All sessions			1st session			2nd session		
	a	b	r^2	a	b	r^2	a	b	r^2
Day 1	1382	476.5	0.321	1330	575.3	0.331	1447	378.3	0.443
Day 2	-566	1522	0.688	-1199	1970	0.814	66.47	1075	0.778
Day 3	710.7	646.1	0.807	772.5	592.4	0.784	642.2	701.9	0.851

Fitts' law represent reaching movement in two dimensional space. Therefore, we can estimate quantitatively reaching movement, if fitts' law is applicable to stroke patients, we can assess the severity easily. In two-dimensional space, finding representative reaching movement model based on fitts' law means that the model is no significant difference among directions. Moreover, fitts' law is partially applicable with stroke patients, the model is significant difference among directions. Therefore, it is difficult to find representative reaching movement model.

As shown in Table. 13, fitts' law is partially available. It will be necessary to take advantage of this study on how to find the model that represents the reaching movement in two-dimensional space.

Ⅴ. CONCLUSION

The purpose of study is to find representative reaching movement model based on fitts' law in two dimensional space. Before we mentioned, finding representative reaching movement model satisfies two conditions. First, Fitts' law is applicable. Second, there is no significant difference among model of each direction. Therefore, we designed experimental protocol in order to investigate two conditions.

For healthy subjects, 7 of 10 subjects satisfied fitts' law. However, 3 subjects who did not satisfy fitts' law satisfied after changed end-effector and there is no significant difference among directions. Therefore, it is able to find the representative reaching movement model. For stroke patients, nobody satisfied fitts' law. But 2 of 4 patients satisfied at specific direction and there is significant difference among directions, so it is unable to find the representative reaching movement model.

Some limitations exist. First, fitts' law was not valid at the smallest target size(W) for healthy subjects. It means that valid range of W may exist. Second, Hand-eye coordination is crucial component at reaching movement. Hand-eye coordination is the coordinated control of eye movement with hand movement, and the processing of visual input to guide reaching and grasping along with the use of proprioception of the hands to guide the eyes. Under our experimental condition, reaching movement by using gimbal was performed by forearm. Furthermore, gimbal was located under robot arm, it is hard to see their arm. If we use the end-effector which is able to treat by hand, we will get the better result.

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요 약 문

뇌졸중 환자의 도달 운동을 통한 피츠의 법칙 검증; 로봇 기반 상지 재활의 가능성 있는 응용

본 논문은 뇌졸중 환자의 도달 운동을 통한 피츠의 법칙 검증을 다룬다. 피츠의 법칙은 난이도 지수(ID, Index of Difficulty)와 시작점으로부터 목표점까지 움직이는데 소요되는 시간 사이의 관계를 표현한 1차 방정식으로, ID는 시작점으로부터 목표점까지의 거리(A)와 목표점의 크기(W)의 함수로 이루어져있다. 피츠의 법칙은 1 차원에서 도달 운동(reaching movement)를 표현한 것인데, 후속 연구들에 의해 2차원 평면에서의 도달 운동으로 확정되어 적용되는 것으로 알려져 있다. 피츠의 법칙을 사용함으로써 도달 운동에 대한 정량적인 평가가 가능하고, 피츠의 법칙이 환자에게 적용 된다면 도달 운동에 대한 평가를 쉽게 할 수 있을 것이다. 따라서 치료 전과 후의 상태 비교도 쉽게 될 것이고, 도달 운동을 사용한 평가가 진행됨으로 평가와 동시에 치료가 가능하다는 장점을 가진다. A와 W에 의해 ID가 변화될 수 있으므로 같은 프로토콜에서 다양한 난이도를 가진 목표점을 제공해줄 수 있기 때문에 환자 맞춤형 치료를 제공해줄 수 있고 더불어 동기부여, 학습효과 방지 등과 같은 부가적인 효과도 기대할 수 있을 것이다.

핵심어: 피츠의 법칙, 도달운동, 로봇기반, 재활, 뇌졸중