Journal of Electromyography and Kinesiology 39 (2018) 120–127

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Improving the test-retest and inter-rater reliability for stretch reflex measurements using an isokinetic device in stroke patients with mild to moderate elbow spasticity

Minki Sin[a,1], Won-Seok Kim[b,1], Kyujin Cho[a], Sungmin Cho[b], Nam-Jong Paik[b,*]

[a] School of Mechanical and Aerospace Engineering, Seoul National University/IAMD, Seoul, Republic of Korea
[b] Department of Rehabilitation Medicine, Seoul National University College of Medicine and Seoul National University Bundang Hospital, Seongnam, Republic of Korea

ARTICLE INFO

Keywords:
Stroke
Muscle Sspasticity
Stretch reflex
Isokinetic
Reliability
Quantification
Electromyography
Torque

ABSTRACT

The conventional tools to measure spasticity exhibited insufficient test-retest or inter-rater reliability. Therefore, the spasticity measurement using an isokinetic device has been proposed to improve these reliabilities of the angle of catch (AoC) measurements; however, this proposal has not been investigated in a standardized manner.

In this study, the comparison of the AoC measurement was performed using two modes (isokinetic and manual motion) to investigate whether the standardized isokinetic motion could increase the reliabilities. Motion consistency was calculated using a newly developed index. To analyze the effect of the motion standardization, AoC were estimated using EMG data for both modes, and to compare the measurement reliability, AoC for isokinetic mode was estimated using both EMG and torque data.

Although the test-retest reliability for manual motion was excellent, the use of isokinetic motion improved it to the level of extremely excellent. Intraclass correlation coefficient (ICC) for the inter-rater reliability of manual motion was 0.788, which was near the lower limit of the excellent. Isokinetic motion improved it to the ICC of 0.890 and 0.931 based on the EMG and torque, respectively.

These improvements in reliabilities reduced the measurement errors, sample size, and need for the same rater in clinical trials.

1. Introduction

The prevalence of post-stroke spasticity ranges from 20% to 40% and is more common in the upper than in the lower limbs (Sommerfeld et al., 2012). Spasticity can cause secondary complications such as pain, contractures and muscular imbalance, resulting in reduced health-related quality of life (Lundström et al., 2008, Sommerfeld et al., 2004).

Several types of treatment can be used for the management of spasticity including physical therapy, heat or cold application, medication and chemo-denervation (Bethoux, 2015). To determine the efficacy of these treatments, accurate quantification of spasticity before and after intervention is required. The Modified Ashworth scale (MAS) is the most commonly used measurement tool in clinical research (Ashford and Turner-Stokes, 2013). However, the inter-rater reliability of MAS is unacceptable in stroke patients and the grading system represents only a nominal measure of resistance to passive movement (Li et al., 2014, Mehrholz et al., 2005, Pandyan et al., 1999).

The Modified Tardieu Scale (MTS) was introduced as a more adequate measure of the spasticity (Patrick and Ada, 2006). The Angle of Catch (AoC), Tardieu's R1, which is measured clinically by sensing the catch during a manual fast stretch of a spastic muscle, represents the velocity-dependent characteristic of spasticity (Boyd and Graham, 1999). However, the MTS also showed limited inter-rater reliability and it is recommended that the same rater perform the test during the follow-up period (Ansari et al., 2008, Biering-Sorensen et al., 2006, Mehrholz et al., 2005). The variability in the MTS between raters can be explained by three factors: (1) errors from goniometry measurements, (2) inter-rater variability of assessment motion profile, (3) inter-rater variability in the sense of catch (van den Noort et al., 2009).

Several studies used objective measurement to overcome the limitation of the conventional tools. Paulis et al. reported that the use of an inertial sensor can increase the inter-rater reliability of MTS by reducing the errors caused by the angle measurements or variabilities in the sense of catch (Paulis et al., 2011). However, this method cannot

* Corresponding author at: Department of Rehabilitation Medicine, Seoul National University College of Medicine, Seoul National University Bundang Hospital, 82, Gumi-ro 173 Beon-gil, Bundang-gu, Seongnam 13620, Republic of Korea.
E-mail address: njpaik@snu.ac.kr (N.-J. Paik).

[1] These authors were equally contributed to the study and preparation of the manuscript.

https://doi.org/10.1016/j.jelekin.2018.01.012
Received 5 November 2017; Received in revised form 5 January 2018; Accepted 29 January 2018
1050-6411/

ScienceDirect

Download Export

Journal of Electromyography and Kinesiology
Volume 39, April 2018, Pages 120-127

Improving the test-retest and inter-rater reliability for stretch reflex measurements using an isokinetic device in stroke patients with mild to moderate elbow spasticity

Minki Sin [a, 1], Won-Seok Kim [b, 1], Kyujin Cho [a], Sungmin Cho [b], Nam-Jong Paik [b]

[a] School of Mechanical and Aerospace Engineering, Seoul National University/IAMD, Seoul, Republic of Korea
[b] Department of Rehabilitation Medicine, Seoul National University College of Medicine and Seoul National University Bundang Hospital, Seongnam, Republic of Korea

Received 5 November 2017, Revised 5 January 2018, Accepted 29 January 2018, Available online 3 February 2018.

Check for updates

Show less

https://doi.org/10.1016/j.jelekin.2018.01.012 Get rights and content

Abstract

The conventional tools to measure spasticity exhibited insufficient test-retest or inter-rater reliability. Therefore, the spasticity measurement using an isokinetic device has been proposed to improve these reliabilities of the angle of catch (AoC) measurements; however, this proposal has not been investigated in a standardized manner.

In this study, the comparison of the AoC measurement was performed using two modes (isokinetic and manual motion) to investigate whether the standardized isokinetic motion could increase the reliabilities. Motion consistency was calculated using a newly developed index. To analyze the effect of the motion standardization, AoC were estimated using EMG data for both modes, and to

standardize the fast passive motion during the assessment between raters. Previous studies used an isokinetic device to resolve the issue of variation of motion assessment (Condliffe et al., 2005, Starsky et al., 2005), without investigating the effect of isokinetic device on inter-rater reliability of AoC measurement compared with manual motion under the experimental conditions that standardized the errors from angle measurements and catch sensing. In addition, although the use of an isokinetic device to measure mild spasticity may not be useful in a clinical setting due to the lower levels of reflex activity during isokinetic motion reported in previous studies investigating lower limb spasticity (Grippo et al., 2011, Rabita et al., 2005), no study has elucidated this phenomenon in mild upper limb spasticity after stroke.

This study was designed to investigate whether the application of an isokinetic device can increase the test-retest and inter-rater reliabilities to measure the AoC elicited by the stretch reflex in a mild to moderate spastic elbow after stroke. We standardized the conditions for AoC measurements via the stretch reflex using surface electromyography [EMG] between the isokinetic passive and manual fast motions based on our system. Therefore, only the effect of standardizing the assessment motion using an isokinetic device between test sessions or raters on reliabilities was investigated in this study.

2. Methods

2.1. Participants

Patients were recruited from May 2015 to December 2015. These subjects were inpatients or outpatients with stroke from four rehabilitation hospitals. The inclusion criteria were as follows: (1) hemiparesis in the upper extremity caused by stroke, (2) 20 years of age or older, (3) elbow joint spasticity in the range of MAS 1-2 in the hemiparetic arm, (4) no previous disease affecting the function of the hemiparetic arm except for the stroke itself, (5) free of cognitive, language, visuospatial, or attention deficits that could prevent the subjects from following experimental procedures, and (6) free of medical conditions that could cause hemodynamic instability. One psychiatrist affiliated with the Department of Rehabilitation Medicine screened the patients. A total of 17 patients who met the above-mentioned criteria and provided their written consent were enrolled and used for the final analysis in this study. This research was approved by the local Institutional Review Board. It was conducted in accordance with the regulatory standards of Good Clinical Practice and the Declaration of Helsinki (World Medical Association Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects, 2008). The baseline characteristics of subjects are summarized in Table 1.

Table 1
Baseline characteristics of subjects (n = 17).

Variable	Result
Age, years, mean (SD)	54.6 (12.2)
Gender, n (%)	
Men	14 (82.4)
Women	3 (17.6))
Days from stroke onset, median (IQR)	722 (1226)
Hemiplegic side, n (%)	
Right	10 (58.8)
Left	7 (41.2)
Stroke type, n (%)	
Ischemic	11 (64.7)
Hemorrhagic	6 (35.3)
Stroke lesion, n (%)	
Cortical	4 (23.5)
Subcortical	13 (76.5)
Brunnstrom stage, median (IQR)	
Arm	4 (1)
Hand	3 (1)
Leg	4 (1)
Muscle Power, median (IQR)	
Elbow flexor	4 (1)
Elbow extensor	4 (1)
MAS, elbow flexor, n (%)	
1	7 (41.2)
1+	5 (29.4)
2	5 (29.4)

Values are mean (SD), number (%) or median (interquartile range).
MAS: Modified Ashworth Scale.

2.2. Experimental design

Subjects sat on a chair and the surface EMG electrodes were attached to the biceps brachii muscle in the hemiparetic arm based on a previous published guideline (Hermens et al., 2000). An EMG instrument (WEMG-8, Laxtha, Daejeon, Korea) was used to measure muscle activity. Afterwards, a customized isokinetic device was applied to the subject's hemiparetic arm. The isokinetic device was a robot with an elbow containing a single degree of freedom (DOF), which was designed for controlled assessment of motion and measurement of quantitative reaction torque simultaneously. Fig. 1 displays the configuration of the experimental setup and the detailed composition of the isokinetic device is in a supplementary file.

The subject's initial posture was set to the shoulder 90 degrees abducted, the forearm was in the neutral position, and the elbow was positioned at 90 degrees in the horizontal plane. The rotation axis of the robot was aligned to the anatomical axis of the elbow. The forearm was fastened to the device by using straps.

The whole experiment comprised four steps. The overall experimental procedure is shown in Fig. 2. In the first step, the isokinetic device extends the elbow passively with 1°/s from the elbow maximal flexed posture until the resistive torque reached a certain level. The final angle was used as the maximal boundary range of motion (ROM) as follows. In the second step, the subject was exposed to a short perturbation to measure the total inertial mass of the isokinetic device and subject. The total inertial mass was calculated from the measured inertia torque. It was used to compensate the inertia force in the following experiments to extract only the reaction torque generated by stretch reflex. The third step was the AoC measurement using the isokinetic device. One rater set up the posture first. The elbow was extended from a maximal flexed angle with constant velocity of 150°/s by the robot. Three sets were performed with a 2-minute rest period between the sets. The final step was the manual AoC measurement by a human rater. After a 5-minute rest period following the isokinetic AoC measurement, the same rater extended the subject's elbow manually, while the subject was still attached to the robotic device, for three times with a 2-minute rest period. During this step, the robotic device was used only as a quantitative measurement tool and controlled to operate as transparent as possible. Ten minutes after completing the tests by one rater, another rater set up the experimental posture again and repeated the third and fourth step as with rater 1. The orders of rater 1 and rater 2 were randomized. The kinematic (angle, velocity), kinetic (torque) and EMG data were recorded during both isokinetic and manual measurements.

2.3. Control algorithm

The detailed control algorithms are in a supplementary file.

2.3.1. Isokinetic experiment step

The isokinetic AoC measurement was designed to simulate the ideal MTS method as closely as possible. The robot implements the isokinetic motion with a predetermined speed in a given ROM until a reaction force greater than a certain threshold level is generated.

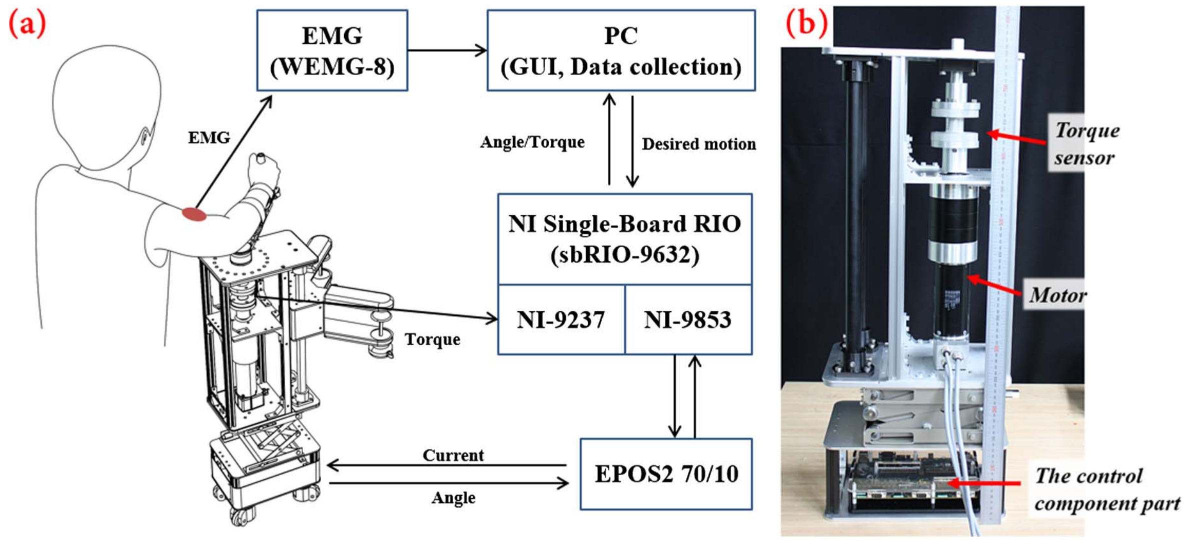

Fig. 1. (a) Configuration of the experimental setup, (b) The detailed view of the robotic part of the isokinetic device.

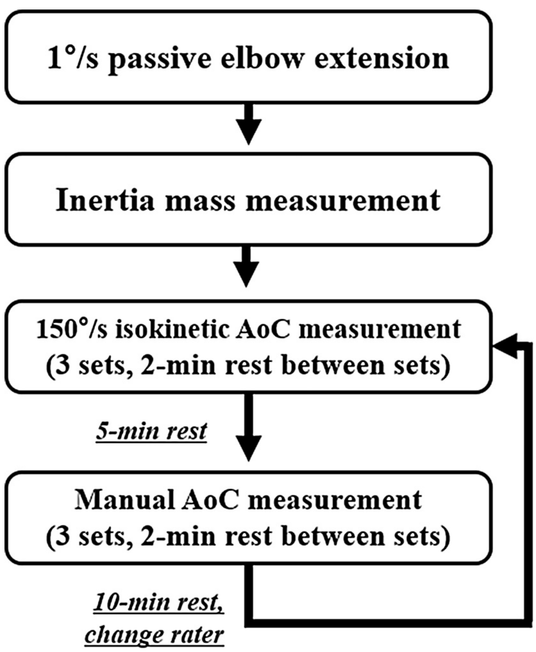

Fig. 2. Experimental procedure for a single subject.

2.3.2. Manual experiment step to measure AoC

The robot was used as a quantitative measurement tool during the manual experiment, thus the robot should be as transparent as possible to create the same condition with a conventional MTS measurement. For this purpose, the isokinetic device was made to be as backdrivable as possible and friction was compensated using a coulomb plus viscous friction model (Jang and Luo, 2014).

3. Analysis

3.1. Quantifying the AoC

3.1.1. Isokinetic input experiment data analysis

Two types of data were used to analyze the AoC in the experiments using the isokinetic device: EMG and torque. Each data was processed and evaluated on a constant basis to identify the AoC.

3.1.1.1. Quantifying the AoC using EMG data. The EMG data was collected at 1024 Hz and corrected for DC bias removal and band-pass filtered from 10 to 450. The raw EMG data were then smoothed using the route-mean-square (RMS) method and amplified 50 times.

The AoC was selected as the starting point of RMS EMG upsurge. Generally, the EMG maximum peak point is used as an AoC. However, the stretch reflex duration and the shape of EMG varied with each patient, and hence, the use of the EMG maximum peak point as an AoC was expected to have a low reliability. Therefore, the EMG upsurge point was selected as the AoC. The AoC selection was performed manually by a third rater who was blind to the order of raters. In the selection process, the normalized EMG measuring less than 0.1 was ignored because it occurred frequently even without a stretch reflex, and the clear inflection point at the start of the peak was selected as AoC. Fig. 3 provides an example of processed EMG and AoC quantification.

3.1.1.2. Quantifying the AoC using torque data. Torque data was collected by applying a low-pass filter of 100 Hz during the experiment. Initially, the isokinetic experiments were designed to stretch the subject's arm with constant speed until the reaction torque exceeded a certain threshold value. The threshold value was determined as a value that can distinguish the transient increase of the torque through several preliminary experiments. However, because of the passive property of the muscles, the reaction torque gradually increased as the angle increased, even though the muscle was not activated (Pisano et al., 2000). Because of this characteristic, it was imperfect to distinguish the AoC by using only the absolute value of the reaction torque. In the case of patients with mild spasticity, there was a possibility that the stretch reflex already occurred before the threshold torque and reached the threshold value by passive stiffness of the muscle. Thus, accurate AoC was determined through additional analysis.

The AoC using the reaction torque was chosen as the point at which the slope of the torque linear regression line changed with a bump in the torque profile. This is because, in the case of a bump, the cause was considered to be due to the sudden stretch reflex, and the change of the linear regression line slope was caused by the passive stiffness change due to the catch. Fig. 4 displays an example of the reaction torque data during the isokinetic experiment and AoC selection based on the torque data. This analysis was also performed by a third rater who was blind to the order of raters.

3.1.2. Manual input experiment data analysis

The catch angle in the manual experiment was analyzed using only

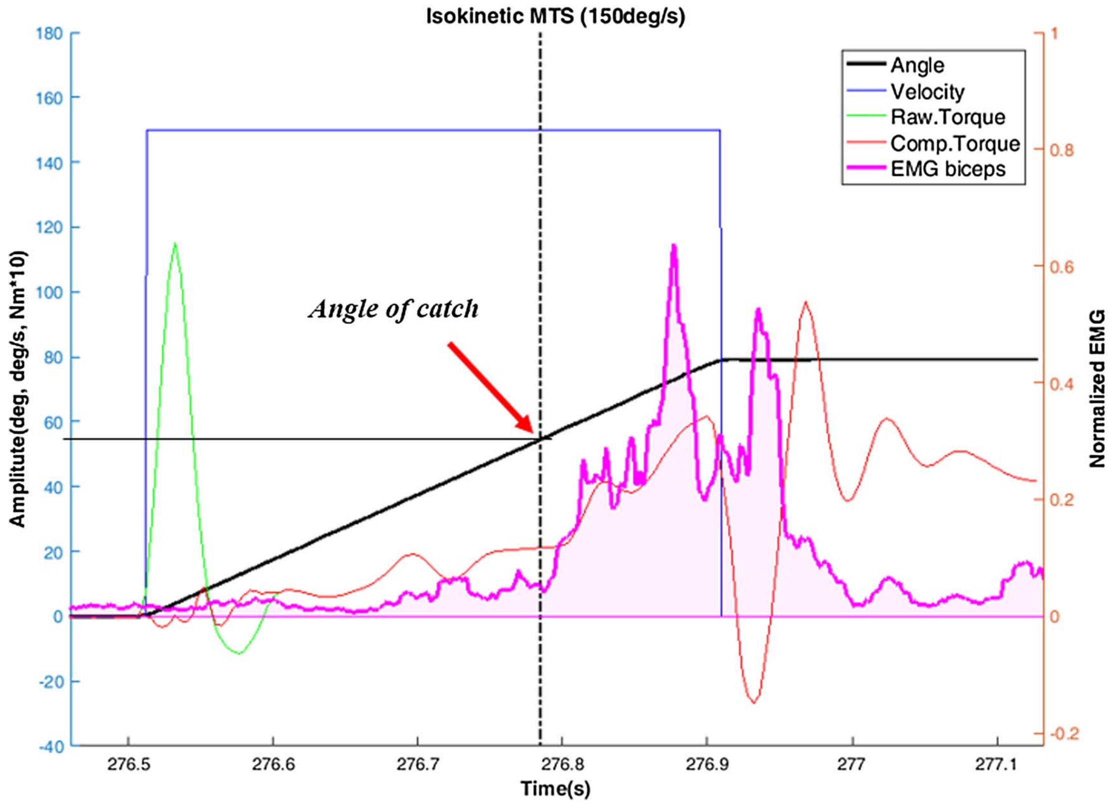

Fig. 3. Isokinetic experiment and quantification of AoC based on EMG data.

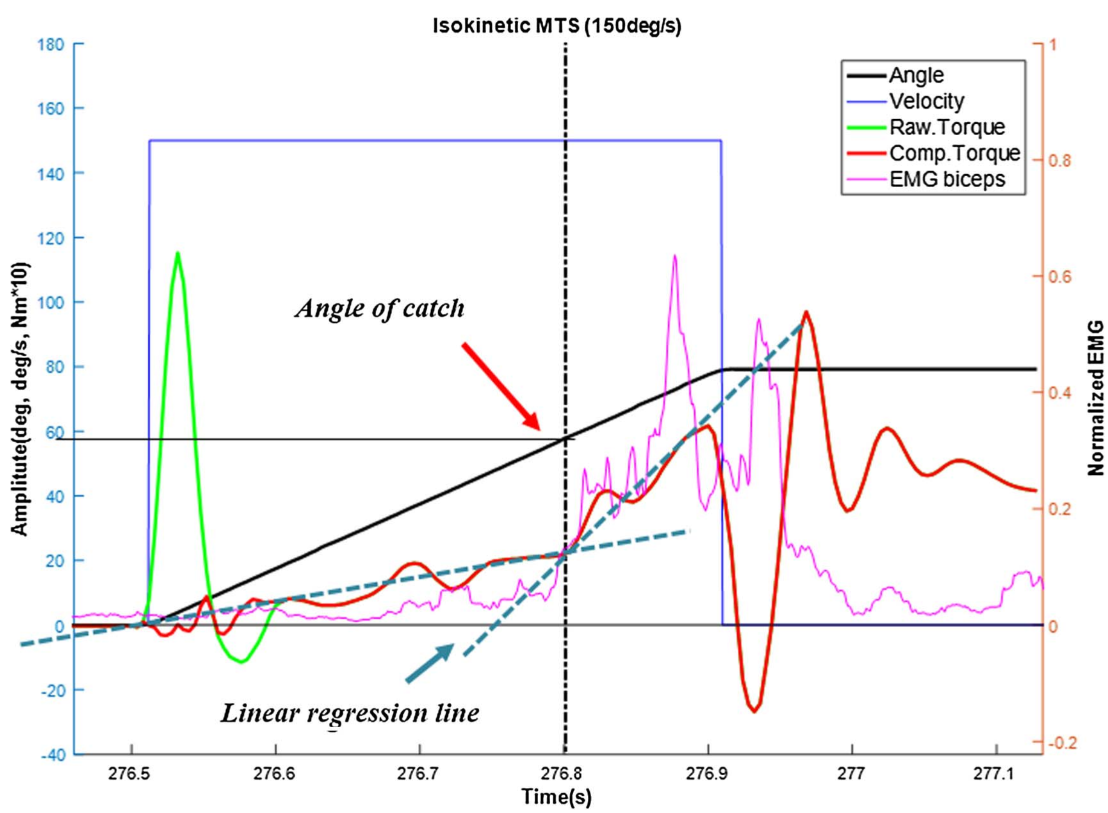

Fig. 4. Isokinetic experiment and quantification of AoC based on reaction torque.

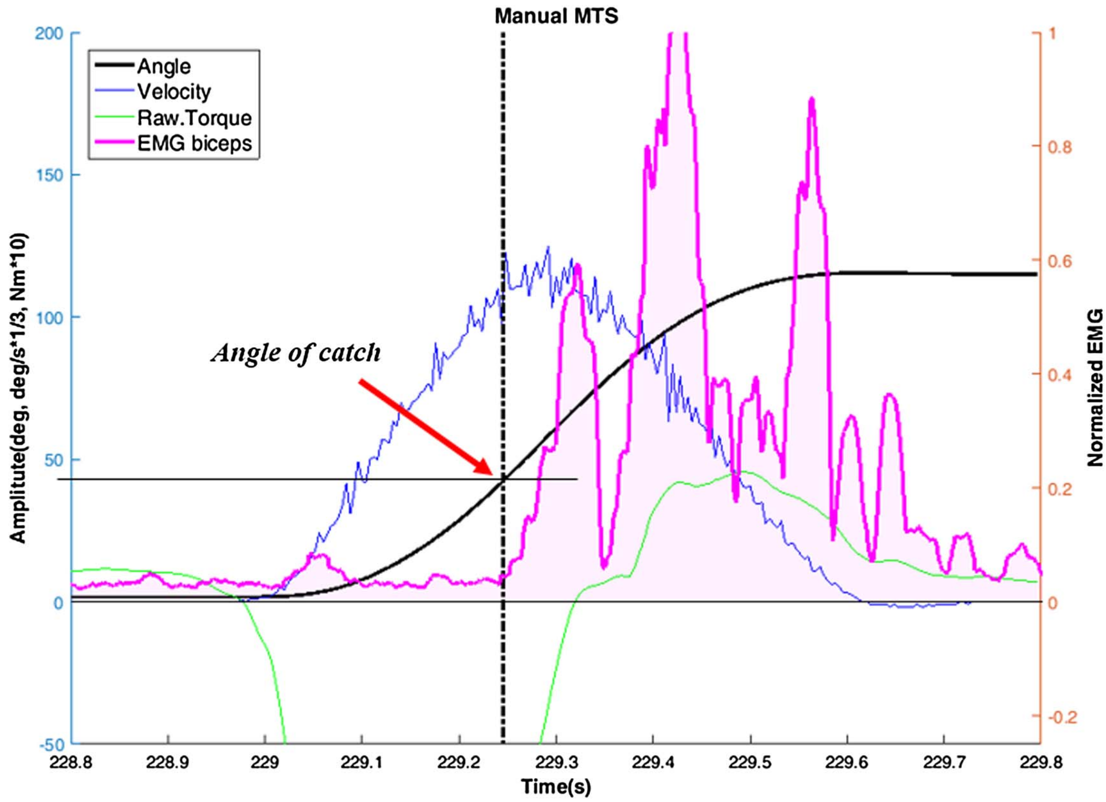

Fig. 5. Manual experiment and quantification of AoC based on EMG data (velocity is expressed in 1/3 scale).

the EMG data using the same criteria as the isokinetic experiment. Fig. 5 exhibits an example of the processed EMG and AoC quantifications.

The torque data measured in the manual experiment was not a pure reaction force generated by the subject because it was affected by the force applied by the rate. Therefore, the AoC analysis using the torque data was not performed because it was hard to guarantee the reliability of the resultant AoC.

3.2. Assessment input normalization

The AoC measurements are affected by the input conditions, such as the assessment speed, and acceleration, and so on. Therefore, quantification of the assessment input is necessary to evaluate not only the AoC reliability but also its consistency. However, no indicators that evaluated the various input factors synthetically have been identified until now. This study suggests an indicator to evaluate the assessment input quantitatively.

The two important points for the evaluation of the assessment input factors include the ideality and the consistency of the input. Previous studies demonstrated that the stretch reflex was affected not only by the velocity but also by acceleration. Therefore, pure isokinetic motion that excludes the influence of the acceleration is ideal to increase the reliability of the AoC measurement. In addition, to evaluate the consistency of the measurements, the similarity of the input should be evaluated. A non-dimensional index derived from the relevant factors was generally used to evaluate the similarity of the profile shape. Therefore, in this study, a non-dimensional index is proposed to normalize the input shape and evaluate the ideality and consistency of the input.

$$\frac{\theta_{\max}-\theta_{\min}}{w_{\max}\cdot\Delta t} \rightarrow \frac{\deg}{\deg/s\cdot s} \tag{1}$$

where θ_{max} and θ_{min} are maximum and minimum angles during the measurement, w_{max} denotes a maximum assessment speed, and Δt is the assessment time from the start to the end of the motion (Fig. 6).

The proposed index yields a score close to 1 if the assessment input is isokinetic, and a score close to 0 if the velocity of the input is inconsistent. The normalized index was calculated and evaluated for each trial during the whole experiment. The index value can be used as an indicator of the consistency of measurement input assigned to the various subjects over the entire trial.

3.3. Statistical analyses

The data of the AoC that was transferred into a measured and normalized input during the second and third tests in each isokinetic and manual experiment were used for statistical analyses. Paired sample t-tests were used to evaluate the differences between the second and third tests in each rater or to test the difference in the averages of second and third tests between two raters. The P-values of less than 0.05 were considered statistically significant. The test-retest and inter-rater reliabilities of an isokinetic device or manual motion with robotic device were computed with an intraclass correlation coefficient (ICC). The AoC and normalized input measured during the second and third tests were used to calculate the ICC for test-retest reliability, and the averages of AoC and normalized input from the second and third tests were used to calculate the ICC for inter-rater reliability. The ICC was used to test the consistency of the time for AoC between the EMG and torque criteria during the third test of isokinetic motion. The correlations between the AoC measured by EMG and torque criteria were investigated by the Pearson correlation coefficient.

The reliability was considered extremely excellent for values exceeding 0.90, excellent for values from 0.75 to 0.90, fair to good for values between 0.40 and 0.75, and poor for values less than 0.40 (Fleiss, 2011). The standard error of measurements (SEM) was calculated to determine the error component of the variance. From the SEM, the smallest detectable difference (SDD) was calculated for test-retest

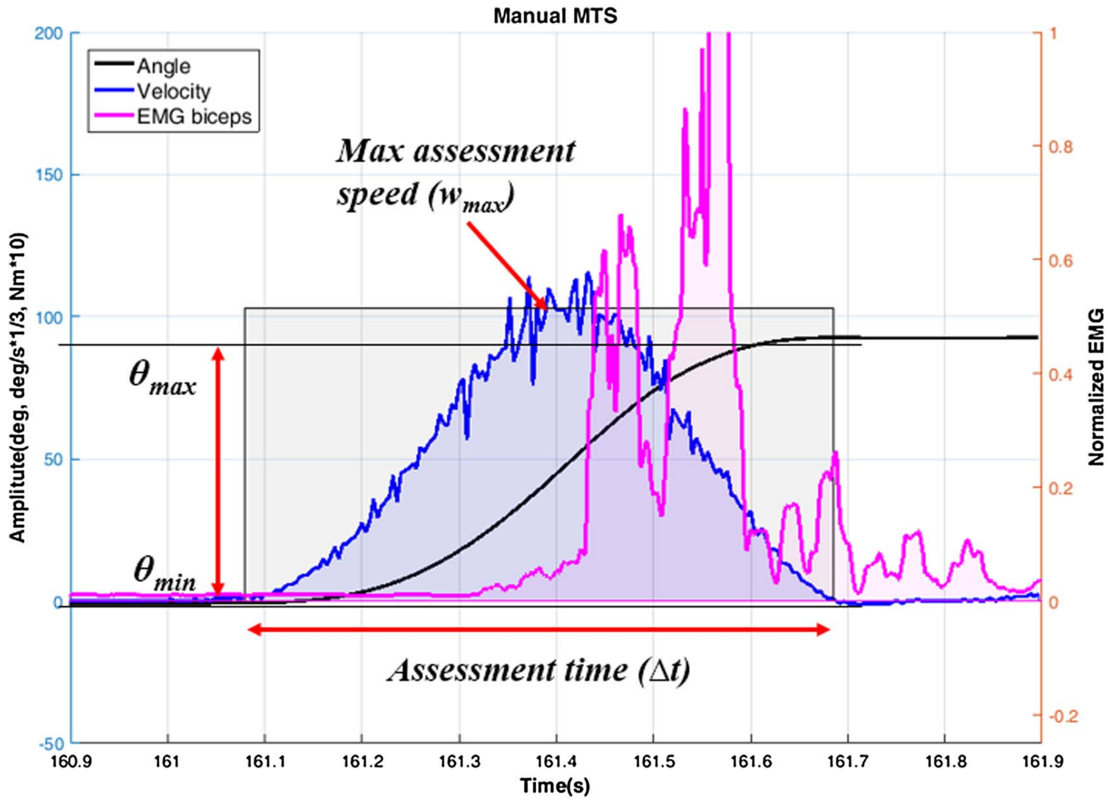

Fig. 6. Elements of the assessment input normalization in the manual experiment (velocity is expressed in 1/3 scale).

data. All statistical analyses were performed using the PASW statistical package (SPSS version 18.0, SPSS, Chicago, IL, USA).

4. Results

4.1. Normalized input evaluation

The normalized index score during isokinetic motion was always one, suggesting that the isokinetic device assigned completely reliable input during the entire trial. The test-retest reliability of the normalized index during manual motion was poor in both rater 1 (ICC [95% CI] = −0.035 [−0.495–0.441]) and rater 2 (ICC [95%CI] = 0.438 [−0.038–0.752]). The inter-rater reliability of the normalized index during manual motion was poor (ICC [95% CI] = 0.148 [−0.344–0.576]).

4.2. Test-retest reliability

Table 2 provides the test-retest reliability for the AoC measurements with isokinetic motion using the EMG or torque criteria and manual motion. The test-retest reliability for manual motion was excellent (ICC = 0.804 (rater 1) and 0.840 (rater 2)). The use of isokinetic motion improved the test-retest reliability to a high degree of excellence based on both the EMG and torque criteria (ICC = 0.929 to 0.997).

4.3. Inter-rater reliability

Table 3 presents the inter-rater reliability for the AoC measurements with isokinetic motion using the EMG or torque criteria and manual motion. The inter-rater reliability for manual motion was excellent but the ICC was 0.788, which was near the lower limit of the excellent range. The isokinetic motion improved the inter-rater reliability to the ICC of 0.890 based on the EMG and to the ICC of 0.931 based on the torque criteria.

4.4. Correlations of AoC and consistency of timing of AoC between the EMG and torque criteria

The AoC that was measured by the EMG signal and the AoC that was measured by the torque during the isokinetic motion displayed a

Table 2
Test-retest reliability results for the angle of catch measured with isokinetic robotic devices and robotic devices with manual motion.

	Test mean (SD)	Retest mean (SD)	*p*	SEM	SDD	ICC (2,1) (95% CI)
Rater 1						
Isokinetic (150°/s) motion with EMG	93.74 (28.35)	90.93 (25.44)	0.216	12.12	33.59	0.948 (0.857–0.981)
Isokinetic (150°/s) motion with torque	90.30 (27.93)	89.61 (27.25)	0.201	3.02	8.37	0.997 (0.992–0.996)
Manual motion with EMG	82.67 (19.11)	82.03 (21.73)	0.838	17.21	47.70	0.804 (0.538–0924)
Rater 2						
Isokinetic (150°/s) motion with EMG	90.77 (28.69)	88.14 (28.34)	0.123	15.10	41.86	0.929 (0.929–0.991)
Isokinetic (150°/s) motion with torque	97.06 (23.47)	94.37 (25.86)	0.192	9.90	27.44	0.959 (0.873–0.987)
Manual motion with EMG	80.96 (21.30)	80.46 (22.81)	0.875	16.94	46.96	0.840 (0.601–0.941)

SEM: Standard error of measurement, SDD: Smallest detectable difference, ICC: Intraclass correlation coefficient, EMG: Electromyography.

Table 3
Inter-rater reliability results for the angle of catch measured with isokinetic robotic devices and robotic devices with manual motion.

	Rater 1 mean (SD)	Rater 2 mean (SD)	*p*	SEM	ICC (2,1) (95% CI)
Isokinetic (150°/s) motion with EMG	88.16 (28.24)	89.46 (28.33)	0.973	17.81	0.890 (0.685–0.961)
Isokinetic (150°/s) motion with torque	94.32 (240.13)	95.71 (24.44)	0.775	12.54	0.931 (0.791–0.978)
Manual motion with EMG	80.81 (18.98)	80.71 (21.17)	0.586	17.50	0.788 (0.493–0.920)

SEM: Standard error of measurement, ICC: Intraclass correlation coefficient, EMG: Electromyography.

significantly high correlation in both raters 1 (Pearson correlation coefficient = 0.937, $p < 0.001$) and 2 (Pearson correlation coefficient = 0.957, $p < 0.001$). The timing of the AoC between the EMG and torque criteria was highly consistent with an ICC of 1 ($p < 0.001$).

5. Discussion

This study is the first examination to investigate the effect of isokinetic fast motion on the test-retest and inter-rater reliability of AoC measurements with an experiment design that standardized the assessment input and catch detection between the isokinetic and manual motion by using the isokinetic device with a surface EMG recording. Previous studies investigated the use of isokinetic devices to measure the spasticity without considering the effect of standardized isokinetic motion on AoC reliability compared with the conventional manual method. (Condliffe et al., 2005, Starsky et al., 2005). In this study, the use of fast isokinetic motion exhibited better test-retest reliability of the AoC than the manual motion in both raters 1 and 2 (Table 2). The inter-rater reliability of AoC displayed an improvement in the isokinetic motion compared to the manual motion (Table 3). The use of the torque criteria for AoC further improved both the test-retest and inter-rater reliabilities of AoC (Tables 2 and 3).

In this study, a normalized input value was proposed to compare the variability of fast motion during AoC measurements. The normalized input during manual experiment show poor test-retest and inter-rater reliabilities. Each subject has different body properties, such as arm mass and muscle stiffness, and the human rater hard to produce consistent, constant motions across repeated tests, which may have led to the poor reliability (Ansari et al., 2008, Mehrholz et al., 2005). On the other hand, the isokinetic device exhibited the normalized input value of 1 with no error, which indicated that a consistent assessment motion was applied to all tests. This high reliability of motion can improve the reliabilities of the AoC measurements (Boiteau et al., 1995, Lamontagne et al., 1998).

One previous study demonstrated that the torque-based AoC measurements had higher inter-rater reliability and intra-rater reliability than EMG-based measurements (Lynn et al., 2013). Although this study did not compare the isokinetic with the manual condition using the torque criterion due to difficulties in separating the force generated by the stretch reflex and the input force by the raters from the measured torque data, the results from the isokinetic motion demonstrated that the use of torque criterion can improve the reliability of AoC more than EMG criterion can do (Tables 2 and 3). Therefore, the combination of torque and isokinetic motion is expected to be a more reliable and convenient tool to measure AoC in stroke patients with spasticity. However, there is a concern that the AoC measured using the torque criteria may not be associated with the stretch reflex, but only with the passive component. To investigate whether the torque criteria reveal the stretch reflex in this study, the AoC based on torque was analyzed manually as the torque upsurge point, because it is difficult to set a constant threshold due to the different torque magnitudes generated by stretch reflex and the gradual increase due to muscle stiffness for each subject. The AoC based on torque criteria was compared with the AoC based on EMG criteria. As a result, the timing of AoC between the EMG and torque criteria was highly consistent and the AoC measured by the EMG and torque criteria exhibited a high correlation, which indicated that the torque criteria may reflect the active stretch reflex.

Unfortunately, an isokinetic device can reduce the frequency of stretch reflex compared with the manual assessment. Grippo et al. reported that no stretch reflex that was recorded by EMG was found during isokinetic knee motion in the patients with MAS 1, 1+; however, the stretch reflex was present in all patients with a spasticity of MAS 2 or 3 (Grippo et al., 2011). Rabita et al. reported that the stretch reflex during isokinetic assessment was less than during the manual assessment of the ankle in adult patients with plantar flexor spasticity, which was described in terms of the differences in acceleration that was beyond the differences in velocity (Rabita et al., 2005). In this study, only those subjects with mild elbow flexor spasticity (MAS 1, 1+, 2) were enrolled and the stretch reflexes recorded by the surface EMG were consistently observed in all subjects during the repeated tests. These results demonstrate that an isokinetic device can be applied to measure AoC even in stroke patients with mild spasticity.

Although this study demonstrated that the use of isokinetic motion increases the test-retest and inter-rater reliabilities of AoC, there are some limitations. First, the posture used in this experiment is different from the conventional MTS measurement. The conventional MTS was made in the absence of shoulder abduction; however, in this study, measurement was performed with the shoulder abducted at 90 degrees. Therefore, our experiment did not completely replicate conventional MTS. However, both the isokinetic and manual experiments were conducted in the same posture with only a different control input, and the stretch reflexes were consistently observed in the EMG that measured the biceps brachii (Figs. 3 and 5). Therefore, this experiment provides a perspective on how the assessment input motion the reliability of an AoC measurement. Second, the resistance of the robot was not completely eliminated during the manual experiment. The robot was used as a measurement device for the manual experiment to accurately measure AoC using a EMG. For this purpose, the robot should be perfectly transparent by compensating the inertia and friction force. However, the robotic device used in this study did not completely compensate for the inertia and friction force, because it used only an encoder that had difficultly measuring the acceleration and simplified friction model. Nevertheless, this limitation may not have a significant effect on the measurement of AoC because the AoC was determined through the EMG analyses instead of the rater's feelings. Third, the AoC analysis has been conducted subjectively by humans. The torque and EMG patterns of the stretch reflex varied slightly between subjects and, in some cases, the transient increase of the torque was unclear, which made it hard to establish criteria for a fully automated analysis. This analysis was performed by third raters who were blind to the information for the order of rater 1 and 2, to minimize the effect of bias on our results.

6. Conclusions

The use of an isokinetic device improved the test-retest and inter-rater reliabilities in stroke patients with mild elbow flexor spasticity, including conditions that standardize the angle measurement and catch feeling. This result may be due primarily to the standardization of the motion by an isokinetic device during elbow extension for spasticity measurement. These improvements in reliabilities by using an isokinetic device can reduce measurement errors, sample sizes in clinical trials, and the need for the same rater to perform multiple tests in a longitudinal study.

Acknowledgements

This study was supported by the Seoul National University Bundang Hospital Research Fund (02-2012-052), Korea and National Research Foundation of Korea (NRF) Grant funded by the Korean Government (A100249).

Authors declare no conflicts of interest except the grant.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jelekin.2018.01.012.

References

Ansari, N.N., Naghdi, S., Hasson, S., Azarsa, M.H., Azarnia, S., 2008. The Modified Tardieu Scale for the measurement of elbow flexor spasticity in adult patients with hemiplegia. Brain Inj. 22, 1007–1012.

Ashford, S., Turner-Stokes, L., 2013. Systematic review of upper-limb function measurement methods in botulinum toxin intervention for focal spasticity. Physiother. Res. Int. 18, 178–189.

Bethoux, F., 2015. Spasticity management after stroke. Phys. Med. Rehabil. Clin. N Am. 26, 625–639.

Biering-Sorensen, F., Nielsen, J.B., Klinge, K., 2006. Spasticity-assessment: a review. Spinal Cord. 44, 708–722.

Boiteau, M., Malouin, F., Richards, C.L., 1995. Use of a hand-held dynamometer and a Kin-Com® dynamometer for evaluating spastic hypertonia in children: a reliability study. Phys Ther. 75, 796–802.

Boyd, R.N., Graham, H.K., 1999. Objective measurement of clinical findings in the use of botulinum toxin type A for the management of children with cerebral palsy. Eur. J. Neurol. 6, s23–s35.

Condliffe, E.G., Clark, D.J., Patten, C., 2005. Reliability of elbow stretch reflex assessment in chronic post-stroke hemiparesis. Clin. Neurophysiol. 116, 1870–1878.

Fleiss, J.L., 2011. Design and Analysis of Clinical Experiments. John Wiley & Sons.

Grippo, A., Carrai, R., Hawamdeh, Z., Falsini, C., Aito, S., Pinto, F., et al., 2011. Biomechanical and electromyographic assessment of spastic hypertonus in motor complete traumatic spinal cord-injured individuals. Spinal Cord. 49, 142–148.

Hermens, H.J., Freriks, B., Disselhorst-Klug, C., Rau, G., 2000. Development of recommendations for SEMG sensors and sensor placement procedures. J. Electromyogr. Kinesiol. 10, 361–374.

Jang, H.-Y., Luo, Y.-S., 2014. Compensation and estimation of friction by using on-line input estimation algorithm. J. Tribol. 136, 021605.

Lamontagne, A., Malouin, F., Richards, C.L., Dumas, F., 1998. Evaluation of reflex-and nonreflex-induced muscle resistance to stretch in adults with spinal cord injury using hand-held and isokinetic dynamometry. Phys. Ther. 78, 964–975.

Li, F., Wu, Y., Li, X., 2014. Test-retest reliability and inter-rater reliability of the Modified Tardieu Scale and the Modified Ashworth Scale in hemiplegic patients with stroke. Eur. J. Phys. Rehabil. Med. 50, 9–15.

Lundström, E., Terént, A., Borg, J., 2008. Prevalence of disabling spasticity 1 year after first-ever stroke. Eur. J. Neurol. 15, 533–539.

Lynn, B.-O., Erwin, A., Guy, M., Herman, B., Davide, M., Ellen, J., et al., 2013. Comprehensive quantification of the spastic catch in children with cerebral palsy. Res. Dev. Disabil. 34, 386–396.

Mehrholz, J., Wagner, K., Meißner, D., Grundmann, K., Zange, C., Koch, R., et al., 2005. Reliability of the Modified Tardieu Scale and the Modified Ashworth Scale in adult patients with severe brain injury: a comparison study. Clin. Rehabil. 19, 751–759.

Pandyan, A., Johnson, G., Price, C., Curless, R., Barnes, M., Rodgers, H., 1999. A review of the properties and limitations of the Ashworth and modified Ashworth Scales as measures of spasticity. Clin. Rehabil. 13, 373–383.

Patrick, E., Ada, L., 2006. The Tardieu Scale differentiates contracture from spasticity whereas the Ashworth Scale is confounded by it. Clin. Rehabil. 20, 173–182.

Paulis, W.D., Horemans, H.L., Brouwer, B.S., Stam, H.J., 2011. Excellent test–retest and inter-rater reliability for Tardieu Scale measurements with inertial sensors in elbow flexors of stroke patients. Gait Posture. 33, 185–189.

Pisano, F., Miscio, G., Del Conte, C., Pianca, D., Candeloro, E., Colombo, R., 2000. Quantitative measures of spasticity in post-stroke patients. Clin. Neurophysiol. 111, 1015–1022.

Rabita, G., Dupont, L., Thevenon, A., Lensel-Corbeil, G., Pérot, C., Vanvelcenaher, J., 2005. Differences in kinematic parameters and plantarflexor reflex responses between manual (Ashworth) and isokinetic mobilisations in spasticity assessment. Clin. Neurophysiol. 116, 93–100.

Sommerfeld, D.K., Eek, E.U.-B., Svensson, A.-K., Holmqvist, L.W., von Arbin, M.H., 2004. Spasticity after stroke. Stroke 35, 134–139.

Sommerfeld, D.K., Gripenstedt, U., Welmer, A.-K., 2012. Spasticity after stroke: an overview of prevalence, test instruments, and treatments. Am. J. Phys. Med. Rehabil. 91, 814–820.

Starsky, A.J., Sangani, S.G., McGuire, J.R., Logan, B., Schmit, B.D., 2005. Reliability of biomechanical spasticity measurements at the elbow of people poststroke. Arch. Phys. Med. Rehabil. 86, 1648–1654.

van den Noort, J.C., Scholtes, V.A., Harlaar, J., 2009. Evaluation of clinical spasticity assessment in cerebral palsy using inertial sensors. Gait Posture. 30, 138–143.

Minki Sin received a B.S and Ph.D degree in mechanical and aerospace engineering from Seoul National University, Seoul, Korea, in 2010 and 2017, respectively. He is currently a post-doctoral researcher in the soft robotics research center, Seoul, Korea. His current research interests include rehabilitation robotics, soft wearable robots and robot control.

Won-Seok Kim received B.S degree from Seoul National University College of Medicine, Seoul, Korea in 2004, M.S degree from Graduate School of Public Health, Seoul National University, Seoul, Korea in 2011 and Ph.D degree from Seoul National University College of Medicine, Seoul, Korea in 2016. He is now working as an assistant professor at the Department of Rehabilitation Medicine in Seoul National University Bundang Hospital, Seongnam-si, Gyeonggi-do Korea. He is interested in the researches for the neurorehabilitaion, geriatric rehabilitation and epidemiology related with the disability issues.

Kyujin Cho received B.S and M.S. degrees from Seoul National University, Seoul, Korea in 1998 and 2000, respectively, and a Ph.D. degree in mechanical engineering from Massachusetts Institute of Technology in 2007. He was a post-doctoral fellow at Harvard Microrobotics Laboratory until 2008. At present, he is an associate professor of Mechanical and Aerospace Engineering and the director of Biorobotics Laboratory at Seoul National University. His research interests include biologically inspired robotics, robotic systems using smart actuators, novel mechanisms using smart structures, and rehabilitation and soft wearable robots.

Sungmin Cho received received Ph.D degree in mechanical and aerospace engineering from Seoul National University, Seoul, Korea, in 2016. He is currently a post-doctoral researcher at the Department of Rehabilitation Medicine in Seoul National University Bundang Hospital, Seongnam-si, Gyeonggi-do Korea. His research interests are in computer graphics, natural interface and rehabilitation engineering.

Nam-Jong Paik received B.S, M.S and Ph.D degrees from Seoul National University College of Medicine, Seoul, Korea in 1990, 1995 and 2000, respectively. At present, he is a professor of Department of Rehabilitation Medicine, Seoul National University of College of Medicine and is working at Seoul National University Bundang Hospital, Seongnam-si, Gyeonggi-do Korea. His research interests are neurorehabilitation and geriatric rehabilitation including stroke rehabilitation, new therapeutic interventions such as neuromodulation, robotic rehabilitation, tele-rehabilitation and virtual rehabilitation.