IEEE Journal of Translational Engineering in Health and Medicine

REHABILITATION DEVICES AND SYSTEMS

Received 3 June 2021; revised 9 September 2021, 1 December 2021, and 2 December 2021; accepted 13 December 2021.
Date of publication 20 December 2021; date of current version 31 December 2021.

Digital Object Identifier 10.1109/JTEHM.2021.3136754

A Novel and Clinically Feasible Instrument for Quantifying Upper Limb Muscle Tone and Motor Function via Indirect Measure Methods

CHIEH-HSIANG HSU[1], YU-CHEN LIN[2], HSIU-YUN HSU[3], HSIAO-FENG CHIEH[4], CHIEN-JU LIN[4], SHIH-FU LING[4], FONG-CHIN SU[1,4], AND LI-CHIEH KUO[1,2,4]

[1]Department of Biomedical Engineering, College of Engineering, National Cheng Kung University, Tainan 70101, Taiwan
[2]Department of Occupational Therapy, College of Medicine, National Cheng Kung University, Tainan 70101, Taiwan
[3]Department of Physical Medicine and Rehabilitation, National Cheng Kung University Hospital, Tainan 70101, Taiwan
[4]Medical Device Innovation Center, National Cheng Kung University, Tainan 70101, Taiwan

CORRESPONDING AUTHORS: L.-C. KUO (jkkuo@mail.ncku.edu.tw) AND F.-C. SU (fcsu@mail.ncku.edu.tw)

This work was supported in part by the Medical Device Innovation Center (MDIC), National Cheng Kung University (NCKU) from the Featured Areas Research Center Program within the framework of the Highest Education Sprout Project by the Ministry of Education (MoE) in Taiwan.

ABSTRACT Objective: Quantifying muscle tone is often based on a tester's subjective judgment in clinical settings. There is, however, a lack of suitable tools that can be used to objectively assess muscle tone. This study thus introduces a reliable, clinically-feasible device, called the Arm Circumference Motor Evaluation System (ACMES), for quantifying the muscle tone of upper limbs without using mechanical torque transducers. Methods: While the ACMES conducts continuously passive arm circumduction motions, the voltage and current of the driving motor is transduced into torque values via a least square approximation. A torque sensor and springs with different spring constants were used for the validity and reliability test in the first part of this study. Fifteen healthy adults and two patients who had experienced a stroke participated in the second part, which was a clinical experiment used to examine the *in-vivo* test-retest reliability and to explore the inspection differences between healthy and patient participants. Results: The results showed that the ACMES has high validity (R^2: ~0.99) and reliability (R^2: 0.96~0.99). The reliability of the ACMES used on human subjects was acceptable (R^2: 0.83~0.85). The various muscle tone patterns could be found among healthy and stroke subjects via the ACMES. Conclusion: Clinically, abnormal muscle tone, which seriously affects motion performance, will be found in many diagnoses, such as stroke or cerebral palsy. However, objectively and feasibly measuring abnormal tone in modern clinical settings is still a challenging task. Thus, the ACMES was developed and tested to verify its feasibility as a measurement system for detecting the mechanical torque associated with muscle tone.

INDEX TERMS Muscle tone, spasticity, upper limb, stroke, indirect measurement.

***Clinical and Translational Impact Statement*—**The ACMES, a clinically-feasible device, was developed and tested to identify its feasibility as a measurement system for detecting the mechanical torque associated with muscle tone in clinical settings.

I. INTRODUCTION

Muscle tone abnormalities are commonly seen in patients with upper motor neuron lesions, including patients having experienced a stroke and those with multiple sclerosis, cerebral palsy, traumatic brain injury, etc. Abnormal muscle tone may consist of decreased or increased muscle tone, which is called hypotonia and hypertonia, respectively [1], [2]. Both flaccid hypotonic muscle and spastic hypertonic muscle may cause movement deficiencies and subsequently interfere with carrying out daily tasks. Muscle spasticity is one of the major problems for stroke patients. The prevalence of spasticity has been reported in 19% to 42.6% of stroke patients [3]–[5]. For clinicians, the treatment of abnormal muscle tone remains an important issue [6]–[8].

IEEE Journal of Translational Engineering in Health and Medicine

Assessments of tone abnormalities have been ongoing for approximately six to seven decades. The Modified Ashworth Scale (MAS) and Modified Tardieu Scale (MTS) are two common assessments that have been widely used clinically to classify abnormal muscle tone into different levels or degrees of severity [9]–[11]. However, the use of these methods to determine abnormal muscle tone relies heavily on subjective experience and judgments made by clinicians [11], [13]. The general idea of using these two scales to measure muscle tone is that clinicians use the naked eye or a goniometer to judge the angle of the joint; meanwhile, they manually stretch or bend the subject's joint quickly to induce abnormal muscle tone. A previous study noted that the degree of muscle spasticity in stroke and Parkinsonian patients is related to the stretch speed, where a higher stretch speed may induce more muscle recoiling resistance [12]. However, there are no standard rules for clinicians to follow when attempting to control the speed of the quick-stretch technique.

Several reports have thus mentioned the inadequate reliability and validity of these techniques to represent either hypotonic or hypertonic conditions of patients after a stroke [11], [13]–[16]. Based on these drawbacks and a lack of objective quantification of muscle tone, in some former studies, attempts were made to use a motor or robot in conjunction with a torque transducer or electromyograph (EMG) to guide the target joint and limb movements directly and then to measure the triggered spasticity. In several works, servomotors or linear motors were used to guide elbow or wrist joint movements and trigger spasticity. They simultaneously recorded the velocity or position of the joint and the joint reflex torque as well, which was used for quantifying muscle tone based on the difference in the measured torque from the baseline torque [12], [17]–[20]. Some other studies utilized the Biodex Rehabilitation/Testing System or custom measuring systems incorporating EMG or force transducers by actively or passively guiding the limb via clinicians or machines to induce abnormal muscle tone and then quantify it, especially with a focus on determining the level of spasticity [10], [21]–[27]. Inconsistent results between the measured torque and MAS were found among some of these previous reports. Starsky *et al.* [25] found that the peak torque, peak joint stiffness, and onset angle of the reflex torque of the elbow joint correlated well with the Ashworth Scale; however, the results in Alibiglou's report showed that the correlations between reflex slope and the MAS score of both ankle and elbow joints were low [10].

Some of the strengths and disadvantages of the different methods proposed in the above-mentioned works used to either quantify or classify muscle tone abnormalities have also been a topic of debate in the literature. However, the fact is that none of these assessments has been truly adopted in actual clinical practice. Up to the present time, conventional manual tests such as MAS or MTS are still commonly utilized and subjectively interpreted by clinicians. The inter-rater reliability of these two scales has been ranked as poor to moderate (MAS κ = 0.16-0.42; MTS κ = 0.29-0.53), which indicates the existence of measurement bias during the tests [11]. Robotic measurement can lead to obtaining more accurate muscle tone data, but the high cost of the system makes it difficult to make use of in actual clinical settings. The general goal of this study is thus to design a novel, clinically-feasible, reliable assessment device used for quantifying the muscle tone of the upper limb without using mechanical torque transducers.

An intuitive way to quantify torque is the use of torque sensors. The high price of a stable and accurate non-contact torque transducer embedded in the device for medical uses may limit generalization to clinical settings. Using an indirect measurement method to measure torque may improve this limitation. Generally, the concept of the indirect measurement method is collecting the input data and transforming it into pseudo-mechanical data without using a load cell or a torque sensor to detect the actual output mechanical data. An indirect measurement method causes the actuator to become a sensor through the use of a transduction matrix used to convert the input current and voltage into outputted mechanical kinetic data. Previous researchers have used this method to obtain a good match between the finite element results and the measured results when testing the impedance of a cantilever beam [28], [29]. When an impedance sensor is not used, the reduced weight of the whole device may lead to a more precise result. Fu, Ling and Tseng [30] used the indirect method to detect drilling damage without using a torque sensor, where the cost of the hardware was shown to be lower.

Therefore, this research group established a customized Arm Circumference Motor Evaluation System (ACMES) based on indirect measurement methods that require less space and less structural complexity than other alternatives. For the purpose of clinical applications, a high-speed mode is needed to induce muscle spasticity in a stroke patient. Therefore, the ACMES allows continuous arm circumduction motion at three speeds (high/medium/low), where the voltage and the current are recorded and transduced into torque values via a least square approximation. To measure the applicability of this novel device, validity and reliability tests of the system were conducted. To determine the applicability of the device for use in humans, a reliability test was also conducted. This study also was an attempt to investigate differences in the characteristics of the muscle tone of upper extremities in healthy participants and stroke patients via the use of this novel device to ensure the system will be suitable for specific clinical applications.

The following hypotheses were proposed as follows: In terms of stability and the applicability of ACMES, (i) the concurrent validity between the transduction mechanical torque and measured mechanical torque will be greater than 0.9, and (ii) the test-retest reliability with the mechanical spring test will be greater than 0.9. To determine the applicability of ACMES applied on human subjects, (iii) the test-retest reliability will be greater than 0.75.

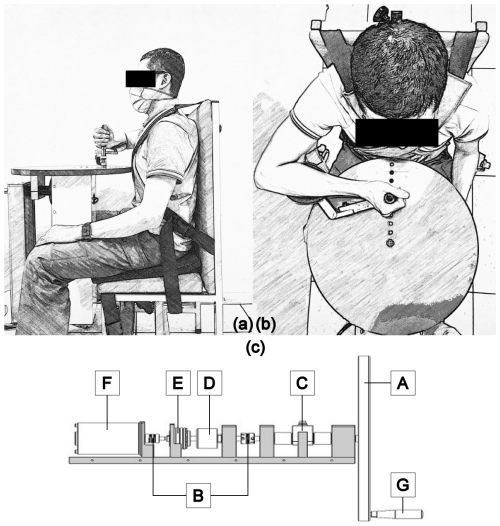


FIGURE 1. The design of the Arm Circumference Motor Evaluation System (ACMES). Fig. 1(a). & Fig. 1(b). show the initial position (0°) of each trial. Fig. 1(c). shows a side view of the mechanism. The frame on which all the components are mounted is shown in gray. (A) a disk, (B) couplings, (C) torque transducer. (D) encoder, (E) reducer, (F) motor, (G) handle.

II. METHODOLOGY

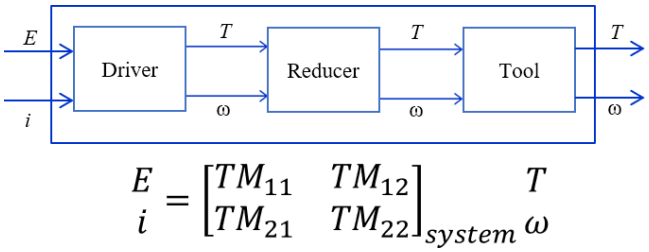
A. THE DEVELOPMENT OF THE ARM CIRCUMFERENCE MOTOR EVALUATION SYSTEM (ACMES)

In this section, the development of the ACMES is described, including the hardware design and the embedding of the indirect measurement method into the system. The validity and reliability are established via a mechanical spring model test and human *in vivo* experiments, respectively.

B. THE ARM CIRCUMFERENCE MOTOR EVALUATION SYSTEM (ACMES)

The ACMES contains two parts, a mechatronic platform and a control system. The mechatronic platform includes an aluminum disk with a diameter of 50 cm, a handgrip, a forearm support, and a columnar box embedded with a motor and measurement units (Fig. 1). The disk itself has several holes arranged from the farthest away to the nearest to the center of the disk. The handgrip can be plugged into a specific hole to fit the subject's arm length when they grasp the handgrip. The horizontal distance from the center of the subject's trunk to the center of the disk is approximately 40 cm to ensure that the subject can remain comfortably seated. The control system includes a personal computer, a data acquisition card, a hall sensor, and a power supply.

The Arm Circumference Motor Evaluation System (ACMES) uses the indirect torque measurement method to assess the characteristics of upper limbs. This device uses a DC motor (2542G, TOKUSHU DENSO, Tokyo, Japan) and a reducer (SHG-20-50-2SO, Harmonic Drive, USA) to drive a disk with a handle that includes a forearm support and a handgrip. The handle can be used to guide the subject's limb in a circular trajectory at different speeds and directions. To prove the validity of the system, a torque transducer TRS600 (FUTEK, California, USA) and an encoder



$$\begin{matrix} E \\ i \end{matrix} = \begin{bmatrix} TM_{11} & TM_{12} \\ TM_{21} & TM_{22} \end{bmatrix}_{system} \begin{matrix} T \\ \omega \end{matrix}$$

FIGURE 2. The mechanism of the transduction matrix of the device.

HTR-HM-15-2500 (HONTKO, Taiwan, ROC) are used to measure the outputted mechanical torque and the angular velocity of the disk. A hall sensor CX-10 (NANA Engineering, Tokyo, Japan) is used to measure the input current. A data acquisition card NI PCI-4462 (NI, Texas, USA) is used to record the input voltage, current, torque, and data from the encoder. A power supply IT-6822 (ITECH, Jiangsu, China) is used to provide the power to drive the motor at different disk rotation speeds and is controlled using a customized program. The system was equipped with two safety devices. If the torque value reaches the set value, the motor will be automatically cut off. If the stop button is pressed, the power to the motor will also be ceased.

C. TRANSDUCTION MATRIX OF THE DEVICE

The operational mechanism of the developed device can be simplified in the form of the block diagram shown in Figure 2. The input voltage and current go through the motor and convert into torque and angular velocity. The torque and angular velocity then go through the reducer and a tool (the disk and the handle) and become an acceptable torque and angular velocity for a human subject. The block diagram is shown in the form of a transduction matrix (Fig. 2)

In Equation (1), the TMs in the matrix are elements of the system, which can be found by using either theoretical derivations or experiments. For a linear system, the transduction matrix can be found using multiple different transduction matrices in all parts. $[TM_{ij}]_{motor}$ is the transduction matrix of the motor; $[TM_{ij}]_{reducer}$ is the transduction matrix for the reducer, and $[TM_{ij}]_{tool}$ is the transduction matrix for the disk and the handle. All these matrices can be combined into a system transduction matrix $[TM_{ij}]_{system}$, as shown in Equation (2), where E is the input voltage; i is the input current; T is the output torque, and ω is the output angular velocity [30], [31].

$$\begin{matrix} E \\ i \end{matrix} = \begin{bmatrix} TM_{11} & TM_{12} \\ TM_{21} & TM_{22} \end{bmatrix}_{motor} \begin{bmatrix} TM_{11} & TM_{12} \\ TM_{21} & TM_{22} \end{bmatrix}_{reducer} \times \begin{bmatrix} TM_{11} & TM_{12} \\ TM_{21} & TM_{22} \end{bmatrix}_{tool} \begin{matrix} T \\ \omega \end{matrix} \quad (1)$$

$$\begin{matrix} E \\ i \end{matrix} = \begin{bmatrix} TM_{11} & TM_{12} \\ TM_{21} & TM_{22} \end{bmatrix}_{system} \begin{matrix} T \\ \omega \end{matrix} \quad (2)$$

The least-square approximation method was used to find the transduction matrix for the specific setting used in this

IEEE Journal of Translational Engineering in Health and Medicine

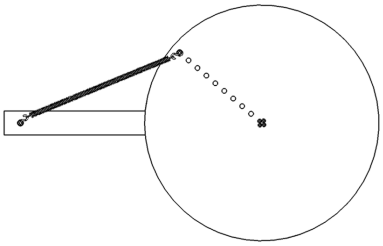


FIGURE 3. The settings for the validity test. A spring was hung on the ACMES with a metal bracket for the purpose of simulating the upper arm motion in human participants using the ACMES.

study, where the voltage, current, corresponding torque, and the corresponding angular velocity collected from the spring and human experiments were used to find the optimal transduction matrix.

D. VALIDITY OF THE SYSTEM

To establish the concurrent validity of the ACMES, a torque sensor was embedded into the system. The measured mechanical torque data collected via the torque sensor, as well as the transduction mechanical torque data collected and converted from the current data and the motor voltage, were recorded simultaneously during the trial. To simulate human muscle, three springs with different k values ($Spring_1 = 46.2$ N/m, $Spring_2 = 60.9$ N/m, and $Spring_3 = 273.4$ N/m) were used to simulate the three different levels of spasticity during the trials. The settings for the validity test are shown in Figure 3. The spring was fixed at both ends with a bearing and then hooked on the bearing with an S-shaped hook. A motor inside the ACMES drove the disk to do the rotation and stretch the spring. The disk completed 15 rotations for each trial. The data from the middle five rotations were recorded. There was a total of six trials in two directions (clockwise and counterclockwise) and three speeds (high = 170 deg/s, medium = 105 deg/s, and low = 40 deg/s). The speed was selected based on a pilot test to determine the most acceptable speed for both the healthy participants and the stroke patients. The high-speed value was chosen based on the findings of previous studies measuring single joint spasticity [12], [19], [25], [32]. The data from the torque sensor was used as the gold standard.

E. RELIABILITY TEST OF THE SYSTEM

To investigate the test-retest reliability of the ACMES, three springs were also used for the purpose of simulating human muscle at different levels of spasticity. The disk was set to complete 15 rotations for each trial. The data from the middle five rotations were recorded.

There were a total of six different conditions with two directions and three speeds. Each condition was repeated three times to investigate the test-retest reliability, where the springs were unmounted and mounted to the disk between three times. A total of 18 trials were carried out to determine the test-retest reliability. The order of the three speed modes and two directions was randomized.

The setting of the reliability test was similar to that used for the validity test but did not incorporate the data from the torque sensor.

F. CLINICAL EXPERIMENT PROCESSES AND DATA ACQUISITION

The participants in this study comprised 15 healthy adults ranging in age from 23 to 35 years and two stroke patients. All healthy participants were right-handed. The MAS scores of the patients ranged from 0 to 3 points (Patient A, elbow flexion/extension: 2/2, wrist flexion/extension: 3/3; Patient B, elbow flexion/extension: 2/1, wrist flexion/extension: 2/0), and the affected hand was the right hand.

Each participant was asked to sit in front of the ACMES and passively grasp the target stick with the dominant hand or involved hand on a forearm support with the hand wrapped around it with a bandage to ensure the hand and forearm remained stable during the trial. All participants were asked not to actively exert strength on any part of the upper limb during the test. A seat belt system was also applied to fasten the trunk during the trial to avoid any effects from compensatory posture. The ACMES drove the disk to guide the participant's hand and upper limb to do the circular motions. While the disk rotated, the wrist, elbow, and shoulder were all driven to allow the upper limb to complete the circular motions. In real human motion, a functional movement is usually accomplished by more than one joint. Compared to MAS or MTS, which can only assess one joint at a time, the design of the ACMES allows the clinician to assess the motor pattern more functionally by measuring the mechanical torque driven by multiple joint motions.

The ACMES provided three trials at three-speed levels in a clockwise direction. The order of the trial speed in the human subject tests moved from the low speed to the high speed due to the fact that a rapid change in the muscle length may potentially induce a muscle stretch reflex leading to muscle or tendon lacerations. In each trial, the disk was rotated 15 times. The data from the middle five rotations were recorded for the test-retest reliability test of the ACMES applied on the human subjects. Also, the motor pattern evidence was also explored to identify possible differences between the normal participants and the stroke patients.

All data were collected after the participants signed an informed consent approved by the Institutional Review Board at National Cheng Kung University Hospital, Taiwan (A-ER-107-317, 2018/10/30). The study was registered at http://www.clinicaltrials.gov (NCT04294407).

G. STATISTICAL ANALYSIS

The data set for the torque output was a waveform type that changed over time. The adjusted coefficient from the multiple determination method (CMD) [34] was thus chosen for the purpose of analyzing the similarities among the waveforms. The CMD or R^2 value ranged from 0 to 1. If the R^2 value was close to 1.00, this indicated that the waveforms were identical. For clinical research studies, coefficient values

TABLE 1. The results of the validity test for the measured mechanical torque and the transduction mechanical torque under different testing conditions.

Direction	Clockwise			Counterclockwise		
Speed	Low	Medium	High	Low	Medium	High
Spring #1	0.99	0.98	0.96	0.99	0.98	0.96
Spring #2	0.99	0.98	0.96	0.99	0.98	0.96
Spring #3	0.99	0.98	0.96	0.99	0.98	0.96

Note. These are the R^2 values calculated by CMD. If the R^2 values were close to 1.00, the data from the measured torque and from the transduction torque were considered perfectly matched.

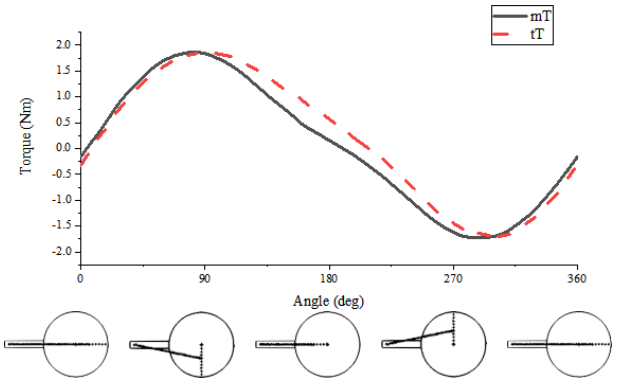


FIGURE 4. The data for the measured and transduction mechanical torque of spring #3 from one round at medium speed in a clockwise rotation. The solid line represents the measured torque (mT), and the dotted line represents the transduction torque(tT). A torque value of 0 means the spring was stretched into its longest status, where, as the degree was increased, the spring became shorter. At 180, the spring was loosened into its shortest status. From 180, the spring was stretched again until it reached 360, which represented its longest status.

between 0.75 and 0.9 and greater than 0.9 are considered indications of good and excellent reliability or consistency, respectively [33]. The CMD method is a method by which to analyze the repeatability of waveform-type data, such as that derived from upper body kinematic data and finger motion analyses [35], [36]. The CMD method was used for the purpose of examining the concurrent validity of the ACMES and its reliability using both springs and human subjects.

III. RESULTS

A. CONCURRENT VALIDITY TEST OF THE ACMES

To calculate the validity of the ACMES, we picked up the data from the five rounds in the middle of the total of 15 rounds for each trial. The R^2 values calculated by the CMD for the concurrent validity test of the measured mechanical torque and the transduction mechanical torque ranged from 0.96 to 0.99 (Table 1). A comparison of the transduction mechanical torque and measured mechanical torque waveforms is shown in Figure 4.

B. RELIABILITY TEST OF THE ACMES

To calculate the reliability of the ACMES, we also picked up the transduction mechanical torque data from the five rounds in the middle of the total of 15 rounds for each trial. The

TABLE 2. The reliability test results for the five rounds of data for transduction mechanical torque in different trials.

Direction	Clockwise			Counterclockwise		
Speed	Low	Medium	High	Low	Medium	High
Spring #1	0.99	0.99	0.99	0.99	0.99	0.99
Spring #2	0.99	0.99	0.99	0.99	0.99	0.99
Spring #3	0.99	0.99	0.99	0.99	0.99	0.99

Note. These are the R^2 values calculated by CMD. If the R^2 values are close to 1.00, the data from each round are considered to be perfectly matched.

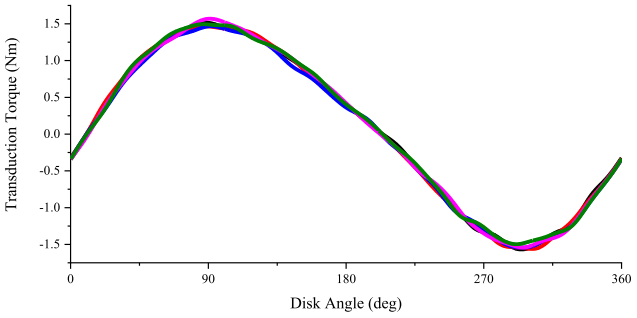


FIGURE 5. The data for the transduction mechanical torque (tT) of spring #1 from five rounds at medium speed with a clockwise rotation.

R^2 values calculated using the CMD for the reliability test of the transduction mechanical torque of these five rounds were nearly 0.99 (Table 2). A comparison of these five successive transduction mechanical torque waveforms is shown in Figure 5.

C. HUMAN SUBJECT TEST

Human subjects include healthy participants and stroke patients. The data collected from the 15 healthy subjects and the two stroke patients were analyzed. The transduction mechanical torque data from the five rounds in the middle of each trial were also picked up from the healthy subjects to examine the repeatability of the ACMES for the *in vivo* test. The transduction mechanical torque data from the healthy subjects and patients were plotted to compare the muscle reactions under different speed conditions.

D. RELIABILITY OF ACMES IN HEALTHY SUBJECTS

The CMD method was used to calculate the test-retest reliability in order to investigate the repeatability of the ACMES on human subjects. The results showed that the R^2 values calculated by the CMD ranged from 0.83 to 0.85 (Table 3).

E. COMPARISON OF THE HEALTHY SUBJECTS AND STROKE PATIENTS USING THE ACMES

The transduction mechanical torque data from the 15 healthy subjects and the two stroke patients were recorded. The transduction mechanical torque waveforms for the two groups are shown in Figure 6. The results showed that the transduction mechanical torque of the two patients was generally higher than the torque values of the healthy subjects. A difference

IEEE Journal of Translational Engineering in Health and Medicine

TABLE 3. The repeatability test results for the ACMES when measuring healthy subjects.

Direction	Low		Medium		High	
	M	SD	M	SD	M	SD
Clockwise	0.83	0.17	0.85	0.14	0.84	0.13

Note. These are the R^2 values calculated using CMD. The data were calculated from normal subjects (n=15).

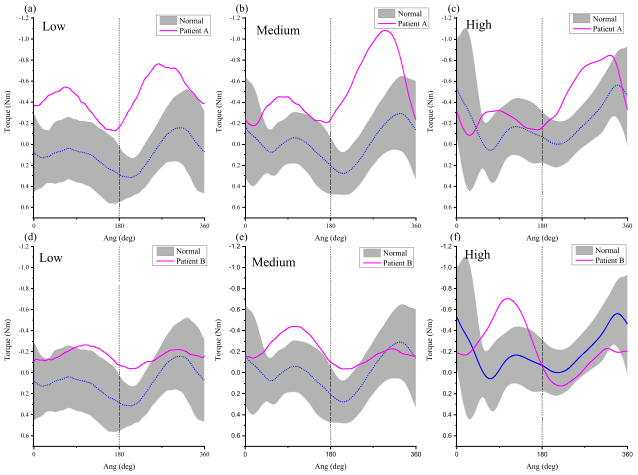


FIGURE 6. The data for the transduction torque (tT) in normal subjects and patients for a comparison of the muscle reaction at different speeds. Figures 6(a), 6(b), and 6(c) are the data for patient A. Figures 6(d), 6(e), and 6(f) are from the data for patient B. The gray area is the data representing the mean value +/- one standard deviation of the performance of normal subjects. Fig. 6(a) and 6(d) show that the tT from the patients is generally higher than from the normal subjects in the low speed mode. Also, Fig. 6(b) and 6(e) show that the tT from the patients is generally higher than from the normal subjects in the medium speed mode. In Fig. 6(c) and 6(f), it can be seen that spasticity in both patients was induced in the high speed mode, but the tT values were not generally higher or lower than was the case for the normal subjects.

between the data for the healthy subjects and patients was clearly found when the x-axis was close to 90°, which was at the timepoint that the subject's elbow angle was guided to an approximate 180° extension. When observing the speed effects during the test, a larger difference in the torque data between healthy subjects and patients was found in the higher speed mode.

IV. DISCUSSION

A. THE DEVELOPMENTAL BACKGROUND OF THE ACMES AND ITS OPERATION

For clinicians, a proper assessment that can be used to quantify muscle tone, especially abnormal muscle tone, is always an important issue that must be done before applying suitable interventions. Although the quick-stretch technique is an easy, common strategy by which clinicians can induce abnormal muscle tone, and the MAS assessment is widely used clinically as well, the inconsistency of the force applied from the examiners and the subjective scoring are concerns that should not be ignored [11], [13]–[16]. To solve the problems related to the current muscle tone scoring system, previous researchers have used EMG, torque, or force sensors to quantify muscle tone [10], [12], [17]–[27]. However, these methods established in previous studies have not been practically used in clinical settings. The high cost of these systems or the low added value of the machines may lower the willingness of either medical device manufacturers or hospitals to develop and purchase these systems. Owing to these existing drawbacks, a novel Arm Circumference Motor Evaluation System (ACMES) based on the indirect measurement methods that is less costly than these other alternative is proposed in this work. The continuous circular motions provided by the ACMES may not only play a role as an evaluation tool for recording abnormal muscle tone in the upper limbs but may also act similarly to a rehabilitation robot in terms of passively allowing continuous elbow flexion and extension to help reduce muscle spasticity through repetitive joint motion exercises [37]–[39]. This has greatly increased its added value.

In addition, in actual human motion, functional upper limb motions require multiple joints working in a coordinated coupling manner [40]. The ACMES potentially allows clinicians to assess spasticity in a more functional way than is the case when using the MAS or modified Tardieu scales.

B. VALIDITY AND RELIABILITY

The ACMES was designed to acquire accurate measurements of muscle tone with an upper arm circular motion that simulates the quick-stretch technique via an indirect measurement method rather than the use of a torque sensor. However, it is crucial to determine the reliability and validity of any newly established system. To ensure that the transduction mechanical torque was valid, a concurrent validity test using a conventional torque sensor as the gold standard was conducted. A high CMD value ($R^2 = 0.99$, represents excellent consistency) in the validation analysis. In the present study, the relationship between the data for transduction mechanical torque and the measured torque indicated whether or not the obtained transduction mechanical torque was precise. A high CMD value (where $R^2 = 0.96$-0.99 represents excellent reliability) in the reliability tests, which represents high repeatability among five successive rounds of the circular motion, indicated that the ACMES exhibited reliably repeated outcomes under various speed and tension conditions.

Although the results of the ACMES repeatability test from the healthy participants appeared to be lower (where $R^2 = 0.83$-0.85 represents good reliability) than the results of the reliability test using the springs, we believe that the result was still acceptable for future clinical applications since quantifying abnormal muscle tone from a patient exhibiting spasticity is much more complex than when using a mechanical spring. In particular, the rapid, high reverse force applied by the patient when inducing spasticity may make the device unstable or break some mechanical components inside the device if the design or structure of the measurement tool is improper. In our case, when a spasm driven by the ACMES occurs during the test, the recoiled force generated by the spasticity may lead to a limited range of joint motion. Therefore, checking the relative position of the

disk, the handgrip, and the upper limb of the patient and then properly adjusting the testing posture is crucial not only for obtaining correct measurements of muscle tone but also to avoid placing the patient at risk during the test. To apply the ACMES on the measurement of the muscle tone for the stroke patients in this study, a senior occupational therapist helped position the patients in the correct testing posture prior to carry out the examination. The data for two patients shown in Figure 6 indicates that the ACMES exhibited the difference in the muscle tone pattern between the healthy subjects and the stroke patients. The findings under the faster speed mode of the ACMES showed obvious differences in the muscle tone patterns between the patients and healthy subjects especially near a 90° disk rotation from the initial position (at the timepoint that the subject's elbow angle was guided to approximately a 180° extension), which is similar to the results when manually performing the quick-stretch test of the elbow flexor in current clinical practice.

C. COMPARISON WITH PREVIOUS STUDIES

From a design perspective, the measurement instruments driven by a mechanical structure reported in previous research [10], [23], [41] typically reveal that devices are typically quite large or involve complex mechanisms related to the device design and construction. The device proposed in this study, however, simplified the driving method to only a motor and a rotary disk. By eliminating the complexity of the structure, the size of the device was decreased. However, the circular motion driven by the device made the process of converting the collected data into the traditional joint angle unintuitive, so it is still necessary to collect more data to establish a norm for further applications.

To quantitively measure muscle tone, many research groups have used EMG, torque, or force sensors to record spasticity data [10], [12], [17]–[27]. Although the results were found to be valid, this approach has still not been widely applied. This study was an attempt to develop a muscle tone acquisition system that can be applied in clinical practice and increase the added value. The force sensors were replaced by a DC motor and a reducer, which were originally embedded inside the machine to drive the disk. Here, added value refers to robotic-type spasticity intervention studies [37], [39], where the design of the ACMES could provide a stable, repeated passive upper arm range of motion exercise at different speeds. However, the efficacy of stretching or continuous passive motion on inducing spasticity remains unclear [42], [43].

The quick-stretch technique is a simple way to induce spasticity. However, previous studies have suggested that using this technique may lead to insufficient repeatability and efficacy [11], [13]–[16]. The ACMES uses a robotic-type design that can continuously produce steady motion and speed that will allow simulation of the same quick-stretch every time. Clinically, abnormal muscle tone will be found in patients with many types of diagnoses, such as stroke, cerebral palsy, and traumatic brain injury, any of which seriously affect motion performance. Treatment for spasticity is always an important issue for these patients. Therefore, an efficient, reliable method to quantify muscle tone is very important to use for confirming intervention efficacy. The ACMES could allow the examiner to easily test for abnormal muscle tone and provides trustworthy results. Also, the design of the continuous circular motion may provide a repeated-passive motion to help with rehabilitation of these patients.

D. LIMITATIONS AND FUTURE STUDIES

Even though the current results showed a difference in the spasticity performance between the stroke patients and the healthy participants, variabilities in muscle tone among individuals cannot be ignored. The torque as measured through a circular motion potentially may be affected by the size or weight of the muscles of the tested limb. This study was aimed toward proving the design concept, constructing the device, and testing its feasibility, so it was only applied to a relatively small number of people in the current stage. It will be necessary to collect more human data under different physical and ergonomic considerations and then to establish a complete norm dataset for the muscle tone of the upper limbs in the future. In addition, the order of the speed modes in the human tests in the present study was not randomized. Therefore, the risk of selection bias in the human subject tests and the effect of the possible decreases in hyper muscle tone in the stroke patients should not be ignored. In addition to establishing a normal database, different examination procedures for muscle tone detection for different types of patients, such as those with multiple sclerosis, spinal cord injuries, or cerebral palsy, may also be required to be determined its use in further clinical practice. Finally, although the ACMES provides to assess the motor pattern more functionally by measuring the mechanical torque driven by multiple-joint motions, some might still be interested in comprehending abnormal muscle tone or motor pattern of an individual joint as a conventionally clinical measure. The present design of the ACMES can only provide driving motion with the entire upper limb of the patients. Thus, the muscle spasticity of each individual joint, such as wrist, elbow, and shoulder, may not be provided via the ACMES with its current design. Developing a method by which to measure the spasticity of individual joints by performing its corresponding joint movement should also be considered in future work.

V. CONCLUSION

Objectively and feasibly measuring abnormal muscle tone in modern clinical settings is still a difficult and challenging task. Thus, in this study, the ACMES was developed, and validity and reliability testing was performed to identify its feasibility as a measurement system for detecting the mechanical torque acting on muscle tone. The findings indicated high validity and reliability, and the differences in muscle tone patterns could also be differentiated among the healthy participants and stroke patients using the system. Therefore, the ACMES can be applied in further research and clinical applications related to spasticity.

IEEE Journal of Translational Engineering in Health and Medicine

ACKNOWLEDGMENT

The authors would like to thank Kwang-Shyan Ho for technical support with manufacturing the ACMES.

REFERENCES

[1] Y. Rivelis, N. Zafar, and K. Morice, "Spasticity," in *StatPearls*. Treasure Island, FL, USA: StatPearls Publishing Copyright, 2020.

[2] S. S. Madhok and N. Shabbir, "Hypotonia," in *StatPearls*. Treasure Island, FL, USA: StatPearls Publishing Copyright, 2020.

[3] D. K. Sommerfeld, E. U.-B. Eek, A.-K. Svensson, L. W. Holmqvist, and M. H. V. Arbin, "Spasticity after stroke," *Stroke*, vol. 35, no. 1, pp. 134–139, Dec. 2004.

[4] P. P. Urban *et al.*, "Occurence and clinical predictors of spasticity after ischemic stroke," *Stroke*, vol. 41, pp. 2016–2020, Sep. 2010.

[5] C. L. Watkins, M. J. Leathley, J. M. Gregson, A. P. Moore, T. L. Smith, and A. K. Sharma, "Prevalence of spasticity post stroke," *Clin. Rehabil.*, vol. 16, no. 5, pp. 515–522, 2002.

[6] F. Miller, "Focal management of spasticity in cerebral palsy," in *Cerebral Palsy*, F. Miller, S. Bachrach, N. Lennon, and M. E. O'Neil, Eds. Cham, Switzerland: Springer, 2020, pp. 611–628.

[7] C. U. Persson, L. Holmegaard, P. Redfors, C. Jern, C. Blomstrand, and K. Jood, "Increased muscle tone and contracture late after ischemic stroke," *Brain Behav.*, vol. 10, no. 2, p. e01509, Feb. 2020.

[8] S. M. Hatem *et al.*, "Rehabilitation of motor function after stroke: A multiple systematic review focused on techniques to stimulate upper extremity recovery," *Frontiers Hum. Neurosci.*, vol. 10, p. 442, Sep. 2016.

[9] R. W. Bohannon and M. B. Smith, "Interrater reliability of a modified Ashworth scale of muscle spasticity," *Phys. Ther.*, vol. 67, no. 2, p. 206, Feb. 1987.

[10] L. Alibiglou, W. Z. Rymer, R. L. Harvey, and M. M. Mirbagheri, "The relation between Ashworth scores and neuromechanical measurements of spasticity following stroke," *J. Neuroeng. Rehabil.*, vol. 5, no. 1, p. 18, 2008.

[11] J. Mehrholz *et al.*, "Reliability of the modified Tardieu scale and the modified Ashworth scale in adult patients with severe brain injury: A comparison study," *Clin. Rehabil.*, vol. 19, no. 7, pp. 751–759, Oct. 2005.

[12] H. M. Lee, Y. Z. Huang, J. J. Chen, and I. S. Hwang, "Quantitative analysis of the velocity related pathophysiology of spasticity and rigidity in the elbow flexors," *J. Neurol. Neurosurgery Psychiatry*, vol. 72, no. 5, pp. 621–629, May 2002.

[13] S. C. Allison, L. D. Abraham, and C. L. Petersen, "Reliability of the modified Ashworth scale in the assessment of plantarflexor muscle spasticity in patients with traumatic brain injury," *Int. J. Rehabil. Res.*, vol. 19, no. 1, pp. 67–78, Mar. 1996.

[14] P. D. Analan and H. Ozdemir, "Assessment of post-stroke biceps brachialis muscle stiffness by shear-wave elastography: A pilot study," *Muscle Ligaments Tendons J.*, vol. 10, no. 3, p. 531, Sep. 2020.

[15] J.-Y. Kim, G. Park, S.-A. Lee, and Y. Nam, "Analysis of machine learning-based assessment for elbow spasticity using inertial sensors," *Sensors*, vol. 20, no. 6, p. 1622, Mar. 2020.

[16] J. Liang, Y. Pei, R. H. Ewoldt, S. R. Tippett, and E. T. Hsiao-Wecksler, "Passive hydraulic training simulator for upper arm spasticity," *J. Mech. Robot.*, vol. 12, no. 4, Aug. 2020, Art. no. 045001.

[17] J. D. Given, J. P. Dewald, and W. Z. Rymer, "Joint dependent passive stiffness in paretic and contralateral limbs of spastic patients with hemiparetic stroke," *J. Neurol. Neurosurg. Psychiatry*, vol. 59, no. 3, pp. 271–279, Sep. 1995.

[18] M. S. Ju, C. C. Lin, J. R. Chen, H. S. Cheng, and C. W. Lin, "Performance of elbow tracking under constant torque disturbance in normotonic stroke patients and normal subjects," *Clin. Biomech.*, vol. 17, nos. 9–10, pp. 640–649, Nov./Dec. 2002.

[19] R. K. Powers, J. Marder-Meyer, and W. Z. Rymer, "Quantitative relations between hypertonia and stretch reflex threshold in spastic hemiparesis," *Ann. Neurol.*, vol. 23, no. 2, pp. 115–124, Feb. 1988.

[20] F. Pisano, G. Miscio, C. Del Conte, D. Pianca, E. Candeloro, and R. Colombo, "Quantitative measures of spasticity in post-stroke patients," *Clin. Neurophysiol.*, vol. 111, no. 6, pp. 1015–1022, Jun. 2000.

[21] M. Gilliaux *et al.*, "Using the robotic device REAplan as a valid, reliable, and sensitive tool to quantify upper limb impairments in stroke patients," *J. Rehabil. Med.*, vol. 46, no. 2, pp. 117–125, Feb. 2014.

[22] H. I. Krebs, N. Hogan, M. L. Aisen, and B. T. Volpe, "Robot-aided neurorehabilitation," *IEEE Trans. Rehabil. Eng.*, vol. 6, no. 1, pp. 75–87, Mar. 1998.

[23] D. J. Reinkensmeyer, L. E. Kahn, M. Averbuch, A. McKenna-Cole, B. D. Schmit, and W. Z. Rymer, "Understanding and treating arm movement impairment after chronic brain injury: Progress with the ARM guide," *J. Rehabil. Res. Develop.*, vol. 37, no. 6, pp. 653–662, Nov./Dec. 2000.

[24] B. D. Schmit, Y. Dhaher, J. P. Dewald, and W. Z. Rymer, "Reflex torque response to movement of the spastic elbow: Theoretical analyses and implications for quantification of spasticity," *Ann. Biomed. Eng.*, vol. 27, no. 6, pp. 815–829, Nov. 1999.

[25] A. J. Starsky, S. G. Sangani, J. R. McGuire, B. Logan, and B. D. Schmit, "Reliability of biomechanical spasticity measurements at the elbow of people poststroke," *Arch. Phys. Med. Rehabil.*, vol. 86, no. 8, pp. 1648–1654, Aug. 2005.

[26] J. M. Hollerbach and T. Flash, "Dynamic interactions between limb segments during planar arm movement," *Biol. Cybern.*, vol. 44, no. 1, pp. 67–77, May 1982.

[27] S. Dehem *et al.*, "Assessment of upper limb spasticity in stroke patients using the robotic device REAplan," *J. Rehabil. Med.*, vol. 49, no. 7, pp. 565–571, Jul. 2017.

[28] H. Xiaoyan and S.-F. Ling, "A sensing and actuating transducer for measuring point impedance to moment," *Measurement*, vol. 43, no. 3, pp. 363–369, Apr. 2010.

[29] S.-F. Ling and Y. Xie, "Detecting mechanical impedance of structures using the sensing capability of a piezoceramic inertial actuator," *Sens. Actuators A, Phys.*, vol. 93, no. 3, pp. 243–249, Oct. 2001.

[30] L. Fu, S.-F. Ling, and C.-H. Tseng, "On-line breakage monitoring of small drills with input impedance of driving motor," *Mech. Syst. Signal Process.*, vol. 21, no. 1, pp. 457–465, Jan. 2007.

[31] H. M. Hondori and L. Shih-Fu, "A method for measuring human arm's mechanical impedance for assessment of motor rehabilitation," in *Proc. 3rd Int. Conv. Rehabil. Eng. Assistive Technol.* Singapore, 2009, pp. 1–4.

[32] A. Thilmann, S. Fellows, and E. Garms, "The mechanism of spastic muscle hypertonus: Variation in reflex gain over the time course of spasticity," *Brain*, vol. 114, no. 1, pp. 233–244. 1991.

[33] T. K. Koo and M. Y. Li, "A guideline of selecting and reporting intraclass correlation coefficients for reliability research," *J. Chiropractic Med.*, vol. 15, no. 2, pp. 155–163, Jun. 2016.

[34] M. P. Kadaba, H. K. Ramakrishnan, M. E. Wootten, J. Gainey, G. Gorton, and G. V. Cochran, "Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait," *J. Orthopaedic Res.*, vol. 7, no. 6, pp. 849–860, 1989.

[35] G. S. Rash, P. P. Belliappa, M. P. Wachowiak, N. N. Somia, and A. Gupta, "A demonstration of the validity of a 3-D video motion analysis method for measuring finger flexion and extension," *J. Biomech.*, vol. 32, no. 12, pp. 1337–1341, 1999.

[36] M. J. Major, R. L. Stine, C. W. Heckathorne, S. Fatone, and S. A. Gard, "Comparison of range-of-motion and variability in upper body movements between transradial prosthesis users and able-bodied controls when executing goal-oriented tasks," *J. Neuroeng. Rehabil.*, vol. 11, no. 1, p. 132, 2014.

[37] K. W. Lee, S. B. Kim, J. H. Lee, S. J. Lee, and S. W. Yoo, "Effect of upper extremity robot-assisted exercise on spasticity in stroke patients," *Ann. Rehabil. Med.*, vol. 40, no. 6, pp. 961–971, 2016.

[38] Y.-J. Chang, J.-N. Liang, M.-J. Hsu, H.-Y. Lien, C.-Y. Fang, and C.-H. Lin, "Effects of continuous passive motion on reversing the adapted spinal circuit in humans with chronic spinal cord injury," *Arch. Phys. Med. Rehabil.*, vol. 94, no. 5, pp. 822–828, May 2013.

[39] C.-L. Wu, M.-H. Huang, C.-L. Lee, C.-W. Liu, L.-J. Lin, and C.-H. Chen, "Effect on spasticity after performance of dynamic-repeated-passive ankle joint motion exercise in chronic stroke patients," *Kaohsiung J. Med. Sci.*, vol. 22, no. 12, pp. 610–617, Dec. 2006.

[40] J. Yu, D. C. Ackland, and M. G. Pandy, "Shoulder muscle function depends on elbow joint position: An illustration of dynamic coupling in the upper limb," *J. Biomech.*, vol. 44, no. 10, pp. 1859–1868, Jul. 2011.

[41] T. Nef, M. Mihelj, and R. Riener, "ARMin: A robot for patient-cooperative arm therapy," *Med. Biol. Eng. Comput.*, vol. 45, pp. 887–900, Sep. 2007.

[42] T. J. Bovend'Eerdt, M. Newman, K. Barker, H. Dawes, C. Minelli, and D. T. Wade, "The effects of stretching in spasticity: A systematic review," *Arch. Phys. Med. Rehabil.*, vol. 89, no. 7, pp. 1395–1406, Jul. 2008.

[43] O. M. Katalinic, L. A. Harvey, and R. D. Herbert, "Effectiveness of stretch for the treatment and prevention of contractures in people with neurological conditions: A systematic review," *Phys. Therapy*, vol. 91, no. 1, pp. 11–24, Jan. 2011.