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Development of Sensor-embedded Instrument for Assessing Impaired Hand Function in Patients with Moderate to Mild Stroke

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We aimed to develop a digitally portable hand assessment instrument, named the C-shaped ring, and to assess the severity of the impairment of hand function using C-shaped-ring-based data for patients with stroke. The C-shaped ring was designed as a C-shaped structure. An inertial measurement unit and an infrared sensor were installed to collect the movement and force torque data. Clinical examinations including hand strength (pinch strength and grip strength), Purdue Pegboard Test (PPT), and Box and Block Test (BBT) were assessed for the outcome measure. Predictors were data collected during the grasping and release of the C-shaped ring with the affected hand. A total of 30 patients participated in this study. The multiple regression analysis explained 41.9, 66.7, 76.4, and 61.2% of the variability in pinch strength, grip strength, and the PPT and BBT results, respectively. In this research, a substantial amount of the variance in the fine dexterity function of C-shaped-ring-based data was observed. The C-shaped design of the C-shaped ring assisted the patients with stroke in performing the grasp-and-release task with the proper hand position, and the spring mechanism allowed the patients to exert grip force actively and release the grip passively.

1. Introduction

Deficits in the upper limb (UL) after stroke are highly prevalent, and residual UL impairments after stroke are the major contributors to limitations in activities of daily living. It has been shown that both hand strength and hand function are good indicators of functional arm recovery in patients with stroke.[(1,2)] In clinics, the dynamometer and pinch gauge are commonly used for assessing hand strength, grip strength and pinch strength.[(3,4)] The Purdue Pegboard Test (PPT) and Box and Block Test (BBT) are also frequently used for measuring hand function.[(3–6)] However, these assessment tools require at least one clinician to be on-site. Such a clinician must also complete a training course before assessing subjects' hand strength and hand function, and assessment results may differ between assessors with various levels of experience.[(3)] Therefore,

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an objective, digital, portable, and accessible instrument for assessing functional arm recovery is required.

Numerous portable instruments have been invented to assess hand function in people with UL impairments due to stroke. A cylindrical grasp device with 14 embedded force sensors and an inertial measurement unit (IMU) was designed for assessing hand function in people with stroke, and device-based data were shown to have moderate correlation with hand dexterity and high correlation with hand strength.(7) Other instruments designed on the basis of glove concepts or other structures have been constructed with wrist hand orthoses, and IMUs and electromyography sensors embedded in these instruments can also provide a quantitative and objective assessment system for patients with stroke.(8,9) However, these instruments may be excessively heavy or visually unattractive, and they may interfere with hand movements. In other studies, an off-the-shelf device containing an IMU has been used to assess the hand function of people with stroke. Although it is lightweight, convenient, and easy to use, it is limited to assessing UL gross motor function.(10,11) Although the IMU has some limitations, it is still an evaluation sensor with great potential. A current trend is to assess the movement of patients with stroke using the kinematic data of hand movements collected from accelerometers and gyroscopes of IMUs. The benefit of using IMUs is that they are portable, cheap, and lightweight. They can also be run on cheap microcontrollers with tiny batteries and low power consumption, and they can easily be integrated with other options on prototyping boards. Therefore, our research integrated an IMU and force sensors to develop a portable and precise hand assessment tool.

The grasp-and-release task is a major UL activity in daily living. However, the hand movements of patients with stroke are often affected and such patients may exhibit clumsy grasping and difficulty in releasing their grasp. In Ma *et al.*'s study, an assistive device with a cylindrical design was used.(7) In another study, it was found that dynamic finger control was required for the valid assessment of hand dexterity.(12) The assessment instrument in our study permitted users to grasp and release dynamically in the correct position with thumb palmar abduction. The instrument was designed to prevent compensatory movement strategies and to detect actual hand function.

Our study had two purposes. The first was to design an assessment instrument, named the C-shaped ring, to assess hand function in patients with moderate to mild stroke. The instrument was designed to ensure correct hand positioning during grasp and release movements and to enable digital data collection for monitoring the quality of movement. A pilot study on the feasibility of the C-shaped ring was completed to compare the performance between the affected and unaffected hands in patients with stroke. The second purpose was to assess the severity of the impairment of hand function based on C-shaped-ring-based data in patients with moderate to mild stroke. Three movement features generated through the use of the C-shaped ring, namely, force, acceleration, and angular velocity, were extracted. A model for analyzing the C-shaped-ring-based data was used to predict hand strength and hand function.

2. Methods

2.1 Participants

The inclusion criteria of our participants were as follows: more than three months since the onset of ischemic or hemorrhagic stroke, unilateral stroke with hemiparesis, the ability to demonstrate at least 20° of active wrist extension and 10° of active finger extension in two fingers, the ability to understand and follow verbal instructions, and having no evident cognitive impairment with MMSE scores greater than 24. The exclusion criteria were as follows: mental disorder or dementia, the diagnosis of orthopedic condition such as an upper extremity fracture, and neuropathy such as in Parkinson's disease. A total of 30 individuals with stroke participated in this study. The mean age of the participants was 59.27 years (SD = 12.08). The sample consisted of 23 men (76.67%) and seven women (23.33%). Most participants were right-handed (n = 27, 90.00%), with only three participants (10.00%) being left-handed. The average time since stroke onset was 30.77 months (±26.52).

The objectives and methods of the study were introduced to the subjects, and written informed consent was provided before participation. The study was approved by the ethics committee of Fu-Jen Catholic University (C109213). The protocol was in accordance with the Declaration of Helsinki and followed institutional ethics board guidelines for research on humans.

2.2 Clinical examination

For this study, several clinical examinations were selected for assessing the affected hand function in patients with stroke. All of them were frequently used in clinical practice at the time of the study. The scores of the clinical examinations were assessed for dependent (outcome) variables and are described as follows. (1) Grip strength: Grip strength was assessed with a digital Jamar dynamometer (Model 12-0112; Fabrication Enterprises, White Plains, NY) with a power grip. The patient was asked to exert maximum force three times, and the average was recorded. (2) Pinch strength: Pinch strength was measured with a pinch gauge.[13] The participants were asked to push the handle of a digital Jamar pinch gauge (model 749805) with a three-jaw chuck grasp while sitting with the elbow in the mid-position on the table. The force was measured in kilograms. The patient was asked to exert maximum power three times at 1 min intervals, and average was recorded. (3) Fine manual dexterity: The PPT includes four subtests (unimanual for right hand, unimanual for left hand, bimanual, and assembly). These help clinicians involved in rehabilitation services to better differentiate fine manual dexterity deficits.[14] In our study, the unimanual subtest with the affected hand (affected hand task) was administered. Performance was scored as the number of pegs placed into the holes in 30 s. Higher scores indicated a better performance of fine manual dexterity by the affected hand. (4) Gross manual dexterity: The BBT was used to assess the gross motor ability of the paretic hand.[15,16] The number of wooden blocks (2.5 cm cubes) transported with the affected hand from one compartment of a box to another within 1 min was taken as the score. Higher scores indicated a better performance of gross manual dexterity by the affected hand. The affected side demonstrated lower power grip strength (18.63 ± 8.28 kg) than did the unaffected side (29.07 ± 8.86 kg). The pinch strength was reduced on the affected side (4.37 ± 1.92 kg) relative to the unaffected side (6.42 ± 1.73 kg). The PPT performance on the affected side showed a lower score (6.49 ± 4.77) than that on the unaffected side (12.03 ± 2.35). In the BBT, the affected hand demonstrated a mean score of 29.97 (±13.63), and the unaffected hand demonstrated a mean score of 41.60 (±9.01).

2.3 C-shaped ring

2.3.1 Design

The C-shaped ring was designed as a rigid C-shaped structure to facilitate standardized grasp-and-release movements while maintaining the thumb in a palmar abduction position. The central axis of the ring body incorporated a torsion spring mechanism, which controlled the closing and opening of the C-shaped gap. This mechanism provided resistance during the grasping phase and assistance during the releasing phase, enabling patients with stroke to actively generate grip force and passively release the grip.

The ring body and the electronics housing box were fabricated using fused deposition modeling (FDM) three-dimensional printing technology, with polylactic acid (PLA) as the printing material. PLA was selected because of its light weight, rigidity, and suitability for rapid prototyping of rehabilitation devices. The prototype had an approximate weight of 400 g, an outer diameter of 80 mm, and an inner diameter of 65 mm. The current version of the device was designed as a fixed-size prototype suitable for adult hands and was not adjustable. All participants recruited in this study were able to grasp the device comfortably in accordance with the inclusion criteria. For future versions, we will consider adjustable designs to accommodate a wider range of hand sizes.

An electronics housing box was mounted on the inner edge of the C-shaped ring. This box contained an Arduino Nano 33 Bluetooth Low Energy (BLE) board, associated wiring, and circuit components. The Arduino Nano 33 BLE board integrates an IMU comprising a triaxial accelerometer and a triaxial gyroscope, which were used to capture linear acceleration and angular velocity signals during grasp-and-release movements. During operation, the Arduino Nano 33 BLE board was powered via a USB connection to a computer, and it subsequently supplied power to the other embedded electronic components. These kinematic data were utilized to extract movement features related to hand function.

In addition to the IMU, an infrared distance sensor was installed within the opening of the C-shaped structure to detect changes in gap distance during grasping and releasing. Variations in this distance were used to estimate the torque force exerted by the affected hand. Therefore, the device had multiple embedded sensors, including an IMU and an infrared sensor, rather than a single sensing element.

The device was powered directly through the Arduino Nano 33 BLE board, which supplied power to the embedded sensors. The same board enabled wireless data transmission via BLE for device control and data reception. The overall design emphasized portability and short-duration use for assessment purposes. The surfaces of the ring that came into contact with the hand were rigid PLA without additional soft padding, as the device was intended for brief assessment tasks rather than prolonged wearing.

The C-shaped ring in an open position and a three-dimensional CAD model are shown in Fig. 1, as well as a clear visualization of the device structure without the hand covering it.

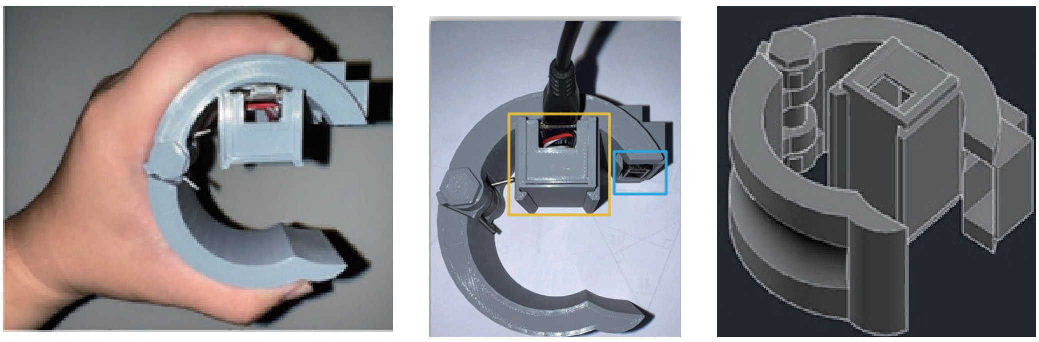
2.3.2 Data collection

The participants were asked to sit in a fixed chair with 0° shoulder flexion, 90° elbow flexion, and a neutral wrist position. Then, they were instructed to grasp (close) the C-shaped ring until the edges at both ends came into contact before releasing (opening) it at a regular pace (1–2 s/cycle). Completing both a grasp (closing) movement and a release (opening) movement was considered one cycle. A total of 10 cycles were performed repeatedly with the affected hand.

For the pilot study, a patient meeting the recruitment conditions was invited to participate in the verification of the feasibility of the C-shaped ring. This participant was asked to perform the above procedure; however, in the pilot study, the C-shaped ring was used to assess both the unaffected hand and the affected hand in turn for comparison of the data.

2.3.3 Signal processing

Signal processing included both force and spatial analyses. In the force analysis, three phases (grasping, holding, and releasing) of force exertion were defined on the basis of the signal trend of torque force (gmf) in the time series. We defined the grasping phase as the first moment the force exceeded zero (first application of force) until the force of 0.69 gmf (first moment approximating the maximal bound) was reached. We defined the holding phase as the first moment of approximating the maximal bound (0.69 gmf) until the last moment of maintaining the maximal bound. The releasing phase began at the last moment of maintaining the maximal



(a) (b) (c)

Fig. 1. (Color online) (a) C-shaped ring (hand-held). (b) C-shaped ring. (c) Three-dimensional graphic rendering produced by autoCAD.

bound and ended when the force returned to or approximated zero. The signals of each phase were processed, and a total of ten cycles were obtained for each participant.

For the spatial analysis, to obtain the most representative triaxial acceleration and angular velocity, the inertial signals were separated into ten cycles and then divided into three phases for each cycle, in accordance with the segmentation principle of force analysis. In the preprocessing stage, the data contained the three phases of each signal, including triaxial acceleration and angular rotation for each cycle (3 × 6), and ten cycles were obtained for each participant.

2.3.4 Experimental parameters (predictive variables)

After signal processing, statistical features were computed to investigate the impact of feature types on hand function. The most common statistical features—e.g., root mean square (*RMS*), *mean*, *max*, and standard deviation (*SD*)—were extracted from the datasets, resulting in 84 features. In the force analysis, the time required to complete each phase in each cycle was called the force time. Each case had 10 values for "force time" because of the execution of ten cycles. We calculated the average of 10 values to find the force time (*mean*) and the standard deviation of the 10 values for the force time (*SD*). Two other parameters in the force analysis, *RMS* (*mean*) and *RMS* (*SD*), were also computed. The force analysis included 12 features across three phases: grasping, holding, and releasing. Each phase (grasping, holding, or releasing) comprised four features: force time (*mean*/*SD*) and *RMS* (*mean*/*SD*).

In the spatial analysis, the *RMS* of the triaxial accelerator and angular velocity for each phase in each cycle were obtained. The maximum value in each phase of each cycle was named *MAX*. The average *RMS* and the standard deviation of *RMS* in ten cycles were calculated, namely, *RMS* (*mean*) and *RMS* (*SD*), respectively. The average *MAX* and the standard deviation of *MAX* in ten cycles were calculated to determine *MAX* (*mean*) and *MAX* (*SD*), respectively. The spatial analysis involved 72 features of acceleration and angular velocity (*x*-, *y*-, and *z*-axes) across three phases (grasping, holding, and releasing), with four variables per phase: *RMS mean*/*SD* and *MAX mean*/*SD*.

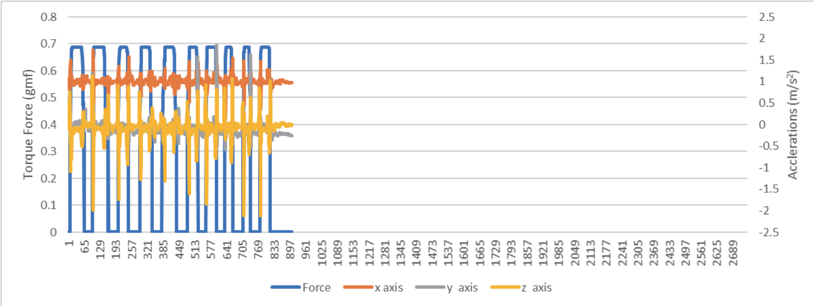
2.4 Statistical analysis

The collected data were analyzed using SPSS/WIN 20.0. The general characteristics of all participants are presented as descriptive statics. To investigate the effects of the variables of the functional evaluation model on clinical examination, multiple regression (stepwise) was used. R-squared values of 0.75, 0.50, and 0.25 for the dependent variables were considered as substantial, moderate, and weak, respectively. The level of significance was set at $p < 0.05$.

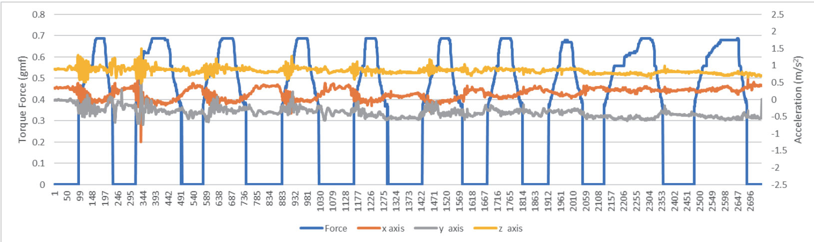
3. Results

3.1 Results of the pilot study

Descriptive information was mainly used to understand the differences in C-shaped-ring-based results between the unaffected and affected hands. Figure 2(a) (unaffected hand) and Fig.



(a)



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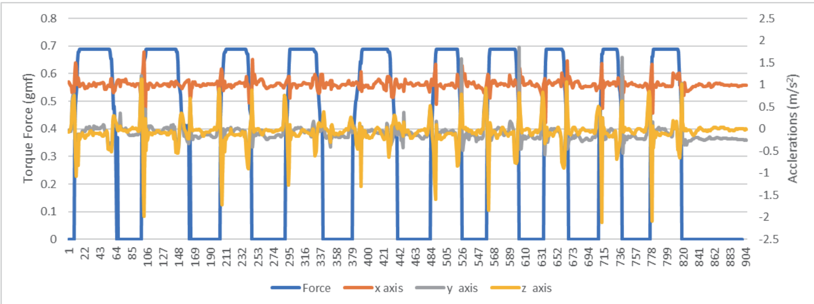

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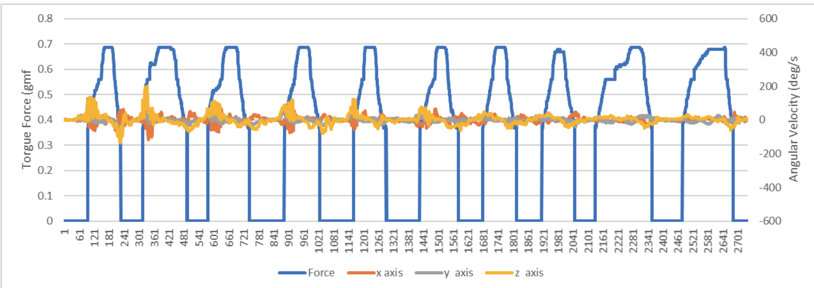
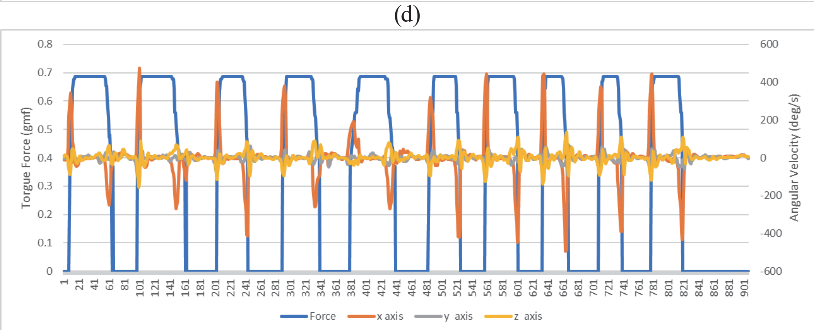


(d)



(e)

Fig. 2. (Color online) Time series data samples of one trial. Fig. 2a shows the force data of the unaffected hand; Fig. 2b shows the force data of the affected hand; Fig. 2c shows the acceleration data of the unaffected hand; Fig. 2d shows the force and angular velocity data of the affected hand; and Fig. 2e shows the force and angular velocity data of the unaffected hand.

2(b) (affected hand) show the data of ten cycles in the same time series (2689 points). The time required for the affected hand to complete 10 grasp-and-release cycles appears to be longer than that for the unaffected hand. To observe the changes in each cycle, Fig. 2(a) was redrawn as Fig. 2(c) in a shorter time series (904 points). The force lines in each cycle in Fig. 2(c) (unaffected hand) represent a smooth upward trend during the grasping phase, a stable trend during the holding phase, and a smooth downward trend during the releasing phase. However, these trends are unstable and obviously uneven in Fig. 2(b) (affected hand). Comparing the acceleration data in Figs. 2(b) and 2(c), it is clear that, in the grasping phase, Fig. 2(b) (affected hand) indicates more instability in all three axes of the data than does Fig. 2(c) (unaffected hand). In Fig. 2(c), the z-axis shows a regular grasp-and-release cycle, but this phenomenon does not appear in Fig. 2(b). The angular velocity data are presented in Fig. 2(d) (affected hand) and 2(e) (unaffected hand). The data in Fig. 2(d) are obviously smaller than those in Fig. 2(e). In Fig. 2(e), the data of the three axes show a regular grasp-and-release cycle, but this phenomenon does not appear in Fig. 2(d). The results demonstrate that the results of force and spatial analyses of the data obtained using the C-shaped ring can clearly show the differences between the unaffected hand and the affected hand.

3.2 Relationship between functional performance and features of C-shaped ring

Multiple regression analysis was conducted on (1) pinch strength, (2) grip strength, (3) subscores of the PPT, and (4) subscores of the BBT as objective variables, and with force data (12 items), acceleration data from the three axes (36 items), and angular velocity data from the three axes (36 items) of each experimental cycle as explanatory variables. The models are listed in Table 1.

4. Discussion

In this study, we developed an instrument named the C-shaped ring for assessing the hand function of patients with stroke. We also explored the predictive model of the C-shaped-ring-based data for hand strength and hand function in patients with stroke. The multiple regression analysis explained 41.9, 66.7, 76.4, and 61.2% of the variability in pinch strength, grip strength, and PPT and BBT results, respectively.

4.1 Substantial fit model for the PPT

In our findings, 76.4% of the variability fell within the substantial range. The model of the C-shaped-ring-based data accounted for a large portion of the variation in the scores on the PPT.[17] This result is consistent with that of the previous research in which a hand evaluation tool was designed using an IMU, which showed a high correlation with PPT scores.[7] The PPT is a sensitive instrument that helps clinicians involved in rehabilitation services to differentiate deficits in fine manual dexterity.[14] Our results suggest that the IMU on the C-shaped ring can provide useful data for detecting fine manual dexterity in patients with stroke.

Table 1
Results of each of the four regression models (stepwise method).

Predictors	*B*	*SE*	*β*	*t*-value	*p*
Outcome measure: Pinch strength with three-jaw chuck grasp	Model: $R^2 = 0.419$, $F = 15.060$, $p < .001$				
Force Time *RMS* (*mean*) in G	−1.642	.542	−.438	−3.028	< .001
Force Time *RMS* (*mean*) in H	1.691	.435	.487	3.885	< .001
A from *X*-axis *MAX* (*mean*) in R	1.298	.285	.528	4.552	< .001
A from *Z*-axis *RMS* (*mean*) in R	−2.910	.715	−.388	−4.070	< .001
Constant	1.634	.578		2.828	.006
Outcome measure: Grip strength	Model: $R^2 = 0.667$, $F = 16.619$, $p < .001$				
Force Time *RMS* (*mean*) in G	53.217	12.697	.362	4.191	< .001
A from *X*-axis *RMS* (*SD*) in H	−4.726	.842	−.623	−5.611	< .001
A from *X*-axis *RMS* (*mean*) in H	.002	.001	.148	2.094	.040
A from *X*-axis *MAX* (*mean*) in R	5.203	1.496	.415	3.478	.001
AV from *X*-axis *RMS* (*mean*) in G	6.185	2.354	.327	2.628	.011
A from *Y*-axis *RMS* (*mean*) in R	12.026	4.258	.267	2.825	.006
AV from *Y*-axis *RMS* (*SD*) in H	−.129	.029	−.470	−4.382	< .001
AV from *Y*-axis *RMS* (*mean*) in H	.406	.109	.396	3.712	< .001
AV from *Z*-axis *RMS* (*mean*) in H	−.446	.098	−.567	−4.546	< .001
AV from *Z*-axis *RMS* (*mean*) in R	.116	.055	.260	2.110	.039
Constant	13.810	8.478		1.629	.108
Outcome measure: Hand performance on PPT	Model: $R^2 = 0.764$, $F = 26.286$, $p < .001$				
A from *X*-axis *RMS* (*SD*) in H	−2.436	0.393	−0.618	−6.194	< .001
A from *X*-axis *RMS* (*mean*) in H	−0.001	0.001	−0.209	−3.585	< .001
A from *X*-axis *RMS* (*mean*) in R	0.002	0.001	0.149	2.545	.013
AV from *X*-axis *MAX* (*mean*) in R	0.018	0.003	0.545	5.563	< .001
A from *Y*-axis *RMS* (*mean*) in H	0.262	0.05`	0.493	4.894	< .001
A from *Y*-axis *RMS* (*SD*) in H	−0.033	0.012	−0.2309	−2.641	.010
A from *Y*-axis *MAX* (*mean*) in G	−0.629	0.280	−0.239	−2.245	.028
AV from *Y*-axis *MAX* (*mean*) in R	−0.059	0.018	−0.347	−3.294	.001
AV from *Y*-axis *RMS* (*mean*) in H	0.097	0.036	0.289	2.687	.001
A from *Z*-axis *MAX* (*mean*) in H	−4.424	1.636	−0.205	−2.704	.001
Constant	−1.049	1.652		−0.635	.527
Outcome measure: Hand performance on BBT	Model: $R^2 = 0.612$, $F = 31.754$, $p < .001$				
A from *X*-axis *RMS* (*SD*) in H	−3.077	1.380	−0.273	−2.229	.029
AV from *X*-axis *MAX* (*mean*) in R	0.094	0.012	0.973	7.682	< .001
AV from *X*-axis *RMS* (*mean*) in R	−0.228	0.090	−0.300	−2.526	.014
A from *Z*-axis *RMS* (*SD*) in R	2.387	0.724	0.441	3.295	.002
Constant	−2.159	4.244		−0.509	.612

Abbreviations: A: acceleration; AV: angular velocity; G: grasping phase; H: holding phase; R: releasing phase.

4.2 Predictive power of the PPT is better than that of the BBT

Our results indicated that the model of C-shaped-ring-based data was highly predictive of scores on the PPT, but it could only explain moderate variance in the scores on the BBT. This difference is not surprising, as the BBT assesses gross manual dexterity, and the PPT, fine manual dexterity. More precisely, fine movements, including tip pinch and manipulation, are required to complete the PPT. Previous research results revealed that the use of compensatory strategies by patients with stroke during assessment was a contributor to inaccurate evaluation outcomes.[7,8,10] Patients with stroke, who may be affected by spasticity, often struggle to position their thumb in palmar abduction. They may adopt compensatory movements such as lateral pinch, forearm pronation, and a thumb–middle finger grasp when picking up objects. To prevent these compensatory movements, three design concepts of the C-shaped ring were as follows: (1) the C-shaped structure ensured that the thumb was positioned in palmar abduction so that the fingers would be in the correct grasp-and-release position throughout the movement process; (2) the spring closing mechanism encouraged patients with stroke to actively exert grasping force against the spring's resistance to complete the grasping motion; and (3) the spring opening mechanism provided opening force to assist patients in completing the release motion. Patients with stroke who are affected by spasticity may experience restricted joint mobility, difficulties in releasing objects, and uncoordinated movements.(17) The resistance and assistance of the spring mechanism may reduce the interference of spasticity during the grasping and releasing phases. Given the highly probable explanation of the variance in PPT outcomes with the model, it is likely that no or few compensatory strategies were used by the patients with stroke during the assessment. Additionally, the design concepts of the C-shaped structure and the spring mechanism are supported.

4.3 Moderate fit model for hand strength

Our results revealed that only moderate amounts of variance in pinch strength and power grip, 41.9 and 66.7%, respectively, could be accounted for by the model of the C-shaped-ring-based data. To measure finger exertion during grasp and release, an infrared sensor was employed to measure the difference in distance at the edges of the C-shaped ring. The force measured by the C-shaped ring was dynamic finger force control. The results of many studies have indicated that dynamic finger force reflects dynamic manipulation, whereas pinch strength and power grip are forms of static contraction.(12,18) This indicates that the force measured by the C-shaped ring was dynamic finger force control, suggesting that the model of the C-shaped-ring-based data could only moderately explain the variance in hand strength.

4.4 Limitations and future directions

While we demonstrated the feasibility and predictive capability of the proposed C-shaped ring for assessing hand function in patients with stroke in this study, several aspects warrant further investigation. First, only a single torsion spring was used in the current prototype. In future studies, springs with different elasticity coefficients should be evaluated to better accommodate various levels of hand strength and motor impairment. Second, although the proposed system showed promising results in predicting hand function, its ability to discriminate among different severities of hand impairment should be further examined in larger-scale studies. Third, the sex distribution of the participants was uneven, which may limit the generalizability of the findings; future research with larger and more balanced samples is therefore recommended.

Moreover, the current C-shaped ring was also implemented as a single-size prototype with fixed dimensions. Although all participants in this study were able to grasp the device comfortably in accordance with the inclusion criteria, adjustable or size-customized designs may further improve usability and applicability across a wider range of hand sizes in future developments.

5. Conclusions

In the current study, we developed a hand assessment instrument for patients with stroke. The C-shaped design ensured that the patients with stroke would perform the grasp-and-release task with the proper hand position, and the spring mechanism allowed the patients to exert grip force actively and release the grip passively. The results indicated that C-shaped-ring-based data could predict hand function with moderate accuracy. Future research should include attempts to investigate ways to differentiate the severities of hand deficits in patients with stroke using the C-shaped ring.

Acknowledgments

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