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RESEARCH

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Development of a quantitative assessment for abnormal flexor synergy index in patients with stroke: a validity and responsiveness study

Daisuke Ito[1], Michiyuki Kawakami[1*], Yuichiro Hosoi[1], Takayuki Kamimoto[1], Yuka Yamada[1], Ryo Takemura[2] and Tetsuya Tsuji[1]

Abstract

Background Arm-lifting movements (shoulder flexion) are essential for upper extremity rehabilitation after a stroke. Abnormal flexor synergy (elbow flexion) is frequently observed during shoulder flexion, impeding functional improvement. However, no quantitative method exists for assessing abnormal flexor synergy. This study investigated the validity and responsiveness of a newly developed index to quantitatively evaluate abnormal flexor synergy.

Methods Participants included 103 patients (mean age: 58.0 ± 10.1 years; 64 men, 39 women) with stroke. Using three-dimensional coordinate data during shoulder flexion obtained from a depth sensor camera, we calculated the abnormal flexor synergy based on our developed index. The abnormal flexor synergy index decreases with increasing flexion of the elbow joint during shoulder flexion (the maximum value is 100% without abnormal flexor synergy). The validity of the abnormal flexor synergy index was assessed by analyzing the correlation between the index and both the Fugl–Meyer Assessment of the Upper Extremity (FMA-UE) four-category scores and the Modified Ashworth Scale (MAS) scores for elbow, wrist, and finger flexors, using Pearson's and Spearman's correlation coefficients. Responsiveness was studied in 17 inpatients (mean age: 59.5 ± 8.1 years; 7 men, 10 women) who underwent proximal upper extremity intervention for approximately 3 weeks, evaluating change from admission to discharge using the standardized response mean (SRM).

Results Significant correlations were observed between the abnormal flexor synergy index and FMA-UE scores: A ($r=0.625$, $p<0.001$), B ($r=0.433$, $p<0.001$), C ($r=0.418$, $p<0.001$), and D ($r=0.411$, $p<0.001$), as well as MAS scores for elbow flexors ($r=-0.283$, $p=0.004$) and proximal interphalangeal flexors ($r=-0.201$, $p=0.042$). The highest responsiveness was observed in the FMA-UE A score (SRM = 0.81), followed by the abnormal flexor synergy index (SRM = 0.79).

*Correspondence:
Michiyuki Kawakami
michiyukikawakami@hotmail.com
Full list of author information is available at the end of the article

Conclusions The newly developed index for assessing abnormal flexor synergy demonstrated superior validity and high responsiveness. These results suggest the potential for using this index to evaluate upper extremity function in patients with stroke.

Keywords Stroke, Upper Extremity, Biomechanical Phenomena, Shoulder, Rehabilitation

Background

Stroke is a leading cause of physical disability [1, 2], with upper extremity dysfunction being a primary symptom affecting approximately 70% of patients with stroke [3, 4]. This dysfunction adversely affects daily activities [5] and diminishes health-related quality of life [6]. Stroke survivors often report that the loss of upper extremity function is one of the most distressing long-term outcomes [7]. Consequently, improving upper extremity function is important for stroke survivors and their caregivers.

Rehabilitation of the upper extremity post-stroke requires using the paralyzed limb for training and daily tasks, with functional improvement dependent on the amount of use [8]. Arm-lifting movements (shoulder flexion) are essential for positioning and orienting the hand in the environment [9]. However, after a stroke, pathological co-activation or reciprocal inhibitory changes arise due to central lesions impairing the corticospinal tracts [10]. Specifically, during voluntary single joint movements, excessive and unintended motion occurs in adjacent joints [11, 12]. This stroke-specific abnormal movement is referred to as abnormal synergy. Two main synergies have been identified in the post-stroke upper limb: the flexor synergy, in which shoulder, elbow, and wrist flexion are obligatorily linked, and the opposite extensor synergies [13, 14]. The most common abnormal flexor synergy is elbow flexion during shoulder flexion [15, 16], which is the leading cause of reaching dysfunction [17, 18]. Moreover, this abnormal flexor synergy can lead to long-term issues such as reduced joint mobility and pain, fostering a learned non-use pattern that limits improvement potential in the hemiplegic upper extremity [19]. Therefore, abnormal flexor synergy should be assessed appropriately to safely and effectively rehabilitate the hemiplegic upper extremities.

However, no established method exists for the quantitative assessment of abnormal flexor synergy. The Fugl–Meyer Assessment of the Upper Extremity (FMA-UE), considered the gold standard for evaluating upper extremity motor paralysis, is commonly used to assess abnormal synergistic movements [20], although it is not quantitative. Recently, various quantitative assessment methods for abnormal synergy in the hemiplegic upper limb have emerged. Previous studies have quantified abnormal synergy using different methods. Some used robotic devices to measure elbow torque and stiffness to assess motor impairments, such as spasticity and joint viscoelasticity [21, 22]. Others utilized electromyography to assess abnormal synergy, revealing impaired coordinated movement and muscle activity patterns during upper limb work impairment and dysfunction [23–25]. Further, three-dimensional movement analysis has been used to investigate joint inflexibility and joint connectivity changes [26]. However, these methods typically do not specifically target flexor synergy during shoulder flexion. Furthermore, these methods require extensive preparation, measurement, and analysis time, making them less practical for clinical settings. To eliminate these issues, we developed a specific quantitative assessment method for abnormal flexor synergy during shoulder flexion, which has not been extensively explored in stroke rehabilitation. Moreover, to enhance the clinical feasibility of our study, we used markerless motion capture technology, reducing the complexity and time required for traditional assessments. This offers a more practical and efficient method for routine clinical use. We hypothesized that the developed index would adequately assess abnormal flexor synergy. This study aimed to investigate the validity and responsiveness of a newly developed quantitative assessment method for abnormal flexor synergy in patients with stroke.

Methods

Study design and participants

This retrospective cohort study was conducted according to the STROBE Checklists and included 103 patients with stroke, both inpatients and outpatients, at Keio University Hospital between January 1, 2021, and March 31, 2024. Inclusion criteria were: ≥ 18 years, chronic stroke (>90 d since onset), and concurrent kinematic and upper extremity functional assessments of shoulder flexion. For the responsiveness study, 17 inpatients who underwent proximal upper-extremity interventions (such as robotics and electrical stimulation) for approximately 3 weeks were selected. Kinematic and upper-extremity function assessments were performed at admission and discharge. This study was conducted in accordance with the Declaration of Helsinki and was reviewed and approved by the Ethics Committee of Keio University (Approval number: 20231079). The opt-out method was applied to obtain informed consent in this study.

Data collection

Medical records were reviewed to collect general characteristics, including age, sex, duration from stroke onset, stroke type, and affected side. Participants in the responsiveness analysis also had an extended hospital stay. Clinical measurements of upper extremity function, FMA-UE [27], and Modified Ashworth Scale (MAS) [28] scores were also obtained from medical records. The FMA-UE [27] score measured upper extremity impairment. The FMA-UE includes 30 motor function items and three reflex function items, scored on a 3-point ordinal scale (0=cannot perform, 1=partially performs, and 2=completely performs), with higher scores indicating better motor function (total score: 0–66 points). The FMA-UE was divided into four categories: A, shoulder/elbow/forearm (0–36); B, wrist (0–10); C, hand (0–14); and D, coordination/speed (0–6). The MAS [28] measured muscle spasticity of the elbow, wrist, and finger flexors (metacarpophalangeal and proximal interphalangeal [PIP] flexors). This is an ordinal scale with a 6-grade criterion (0, 1, 1+, 2, 3, and 4), where higher scores indicated more severe spasticity.

Kinematic analysis

Azure Kinect DK (Microsoft) analyzed hemiplegic shoulder flexion. The test-retest reliability [29] of using Kinect for patients with stroke has been established. Participants sat approximately 2.5 m from the Kinect sensor and performed the maximal shoulder flexion task twice, with their elbows extended as far as possible. The recordings were taken with the Kinect positioned at a height of 1 m. The Kinect data were collected from a dedicated computer.

As preprocessing, three-dimensional coordinate data for the shoulder [*Sx*, *Sy*, *Sz*], elbow [*Ex*, *Ey*, *Ez*], and hand [*Hx*, *Hy*, *Hz*] were acquired. The three-dimensional coordinate data were extracted using dedicated software (ICpro-K2; Hu-tech Co., Ltd., Tokyo, Japan). Spline interpolation was applied to address missing data points. The data were smoothed using a second-order Butterworth filter with a cut-off frequency of 5 Hz and exported as CSV files.

Second, the shoulder flexion angle was calculated from the three-dimensional vectors [*Sx*, *Sy*, *Sz*] and [*Ex*, *Ey*, *Ez]*. The shoulder-floor vertical vector $\overrightarrow{Sf}\,[0,\ 0,\ 0 - Sz]$ and the shoulder-elbow vector $\overrightarrow{SE}\,[Ex - Sx,\ Ey - Sy,\ Ez - Sz]$ were calculated. The shoulder flexion angle θ between $\overrightarrow{Sf}$ and $\overrightarrow{SE}$ was calculated using formula (I) Furthermore, the flexor synergy parameter was derived from the three-dimensional coordinates of the shoulder (*Sx*, *Sy*, *Sz*), elbow (*Ex*, *Ey*, *Ez*), and hand (*Hx*, *Hy*, *Hz*) using formula (II) In formula II, the maximum value is 100% because the denominator and numerator are equal during elbow extension. In contrast, this value decreases as elbow flexion increases during shoulder flexion, due to the proximity of the shoulder and hand.

$$\theta = \cos^{-1}\left[\frac{\overrightarrow{Sf}\cdot\overrightarrow{SE}}{\left|\overrightarrow{Sf}\right|\left|\overrightarrow{SE}\right|}\right] \times (180/\pi) \tag{I}$$

$$\frac{\sqrt{(Hx-Sx)^2+(Hy-Sy)^2+(Hz-Sz)^2}}{\sqrt{(Ex-Sx)^2+(Ey-Sy)^2+(Ez-Sz)^2}+\sqrt{(Hx-Ex)^2+(Hy-Ey)^2+(Hz-Ez)^2}} \times 100(\%) \tag{II}$$

Finally, the area under the curve of the flexor synergy parameter from the start of the exercise to maximum shoulder flexion was calculated. To identify the starting point (X_0) of shoulder flexion, the shoulder flexion angular velocity was determined, and the first instance at which the shoulder flexion angular velocity was continuously positive was noted. Furthermore, the maximum shoulder flexion point (X_{max}) was identified. Next, the time from the starting movement point (X_0) to the maximum shoulder flexion point (X_{max}) was normalized between 0.0 and 1.0 to calculate "X_i". Additionally, "Y_i", the flexor synergy parameter, was calculated using formula II, which was derived from the start of the movement (X_0) to maximum shoulder flexion (X_{max}). The abnormal flexor synergy index was calculated using formula III. This index has a maximum of 100%, with smaller values indicating a higher ratio of abnormal flexor synergy during shoulder flexion.

$$\sum_{i=1}^{n} \frac{(X_i - X_{i-1})(Y_i + Y_{i-1})}{2}\% \tag{III}$$

Statistics analyses

The validity of the abnormal flexor synergy index was assessed by analyzing the correlation between the index and both the FMA-UE four-category scores and individual MAS scores. Pearson's correlation coefficient was used to analyze the relationship between the abnormal flexor synergy index and FMA-UE, while Spearman's correlation coefficient was employed for the correlation between the index and MAS. For the responsiveness analysis, the abnormal flexor synergy index was calculated by matching the maximum shoulder flexion angle to the lower pre- or post-intervention area, and the area under the curve was compared. The responsiveness of each outcome to changes from pre- to post-intervention was determined using the standardized response mean (SRM). The SRM is calculated as the mean difference in scores divided by the standard deviation of paired differences. The magnitude of responsiveness was defined as large for SRM>0.8, medium for SRM between 0.5 and 0.8, and small for SRM between 0.2 and 0.5 [30]. All statistical analyses were performed using the IBM SPSS Statistics software (version 28.0; IBM, Tokyo, Japan). Statistical significance was set at $p \leq 0.05$.

Table 1 General characteristics and upper extremity function of participants in the validity analysis

Characteristics	Values
Number	103
Age (years) [a]	58.0 (10.1)
Sex (men/women) [b]	64/39
Duration from stroke onset (years) [c]	5.5 (2.5–9.9)
Stroke type (hemorrhage/infarction) [b]	68/35
Affected side (right/left) [b]	50/53
FMA-UE, total score (0–66) [a]	27.1 (12.8)
A score (0–36) [a]	19.9 (6.3)
B score (0–10) [a]	2.8 (3.2)
C score (0–14) [a]	3.9 (3.9)
D score (0–6) [a]	0.5 (1.3)
MAS, elbow flexor (0/1/1+/2/3/4) [b]	7/31/55/7/3/0
MAS, wrist flexor (0/1/1+/2/3/4) [b]	10/28/48/12/5/0
MAS, MP flexor (0/1/1+/2/3/4) [b]	49/26/20/7/1/0
MAS, PIP flexor (0/1/1+/2/3/4) [b]	19/15/39/26/4/0
Abnormal flexor synergy index (%) [a]	85.2 (8.5)

[a] mean (standard deviation), [b] number, [c] median (interquartile range)

Abbreviations: FMA-UE, Fugl–Meyer Assessment of the Upper Extremity; MAS, Modified Ashworth Scale; MP, metacarpophalangeal; PIP, proximal interphalangeal

Table 2 Correlation between abnormal flexor synergy index and upper extremity scale

	FMA-UE_A	FMA-UE_B	FMA-UE_C	FMA-UE_D
Abnormal flexor synergy index (%)	0.532**	0.407**	0.355**	0.340**

*p value of <0.05, **p value of <0.01, correlation using Pearson's correlation coefficient

Abbreviation: FMA-UE, Fugl–Meyer Assessment of the Upper Extremity

Results

No adverse events were observed in any participants during the study. Preparation for measurement required minimal time, and the measurement was completed in a few seconds for each participant. The general characteristics and upper extremity function of participants in the validity analysis are listed in Table 1. The mean age of the 103 participants was 58.0 years (standard deviation [SD] = 10.1), comprising 64 men and 39 women. The mean FMA-UE total score and abnormal flexor synergy index were 27.1 points (SD = 12.8) and 85.2% (SD = 8.5), respectively.

Additional File 1: Group differences in the percentage of abnormal movements during shoulder flexion and upper extremity assessments by the severity of upper extremity paralysis.

Table 2 shows the correlation between the abnormal flexor synergy index and upper extremity functional measure. Significant correlations with the abnormal flexor synergy index were found for FMA-UE A ($r = 0.532$, $p < 0.001$), FMA-UE B ($r = 0.407$, $p < 0.001$), FMA-UE C ($r = 0.355$, $p < 0.001$), and FMA-UE D ($r = 0.340$, $p < 0.001$).

Table 3 Correlation between abnormal flexor synergy index and spasticity scale

	MAS_ elbow flexor	MAS_ wrist flexor	MAS_ finger MP	MAS_ finger PIP
Abnormal flexor synergy index (%)	-0.283**	-0.169	-0.066	-0.201*

*p value of <0.05, **p value of <0.01, correlation using Spearman's rank correlation coefficient

Abbreviation: MAS, Modified Ashworth Scale; MP, metacarpophalangeal; PIP, proximal interphalangeal

Table 4 Characteristics of participants in the responsiveness analysis

Characteristics	
Number	17
Age (years) [a]	59.5 (8.1)
Sex (men/women) [b]	7/10
Duration from stroke onset (years) [c]	4.7 (2.0–6.8)
Stroke type (hemorrhage/infarction) [b]	15/2
Paralysis side (right/left) [b]	7/10
Hospital durations (days) [c]	21 (21–24)

[a] mean (standard deviation), [b] number, [c] median (interquartile range)

Table 3 shows the correlation between the abnormal flexor synergy index and spasticity scale. Significant correlations with the abnormal flexor synergy index were found for MAS elbow flexor (r = -0.283, $p = 0.004$) and MAS PIP flexor scores (r = -0.201, $p = 0.042$).

Table 4 presents the characteristics of the 17 participants in the responsiveness analysis. The mean age was 59.5 years (SD = 8.1), with 7 men and 10 women. The median hospital stay duration was 21 d (interquartile range: 21–24 d). Table 5 shows the responsiveness data for each outcome, with the highest responsiveness in the FMA-UE A score (SRM = 0.81), followed by the abnormal flexor synergy index (SRM = 0.79).

Discussion

Abnormal flexor synergy, which is frequently observed in patients with stroke, has no quantitative and convenient assessment method. In the present study, abnormal flexor synergy was quantitatively calculated using a newly developed index. The validity and responsiveness of this index were investigated, revealing mild to moderate correlations with upper extremity functional outcomes, indicating better validity and high responsiveness.

Validity

The abnormal flexor synergy index significantly correlated with all categories of the FMA-UE and MAS elbow and finger flexor scores. The significant correlation with all FMA-UE scores may be attributed to the association between the abnormal flexor synergy index and the severity of upper-extremity dysfunction. Upper extremity

Table 5 Responsiveness of each upper extremity outcome ($n=17$)

Indices of responsiveness	FMA-UE_A	FMA-UE_B	FMA-UE_C	FMA-UE_D	MAS_ elbow flexor	MAS_ wrist flexor	MAS_ MP flexor	MAS_ PIP flexor	Abnormal flexor synergy index
Pre-intervention	16.5 (6.4)	2.1 (3.5)	4.1 (4.9)	0.5 (1.3)	1.8 (0.8)	1.9 (1.1)	0.9 (1.1)	2.1 (1.2)	84.6 (6.9)
Post-intervention	18.0 (7.5)	3.0 (4.3)	4.5 (4.8)	0.5 (1.5)	1.6 (0.7)	1.6 (1.1)	0.6 (1.1)	1.7 (1.3)	88.4 (6.0)
Mean difference	1.47	0.88	0.47	0.06	-0.12	-0.35	-0.24	-0.41	3.82
SD of paired differences	1.81	1.36	0.87	0.24	0.60	0.49	0.83	0.94	4.83
Standardized response mean (SRM)	0.81	0.65	0.54	0.24	-0.20	-0.72	-0.28	-0.44	0.79

Abbreviations: FMA-UE, Fugl–Meyer Assessment of the Upper Extremity; MAS, Modified Ashworth Scale; MP, metacarpophalangeal; PIP, proximal interphalangeal; SD, standard deviation

performance, including segmentation, accuracy, and coordination, was associated with the severity of impairment in patients with stroke [31]. As the FMA-UE is an indicator of upper extremity dysfunction severity, our findings align with this notion. The significant correlation with MAS elbow and finger flexor scores may be attributed to spasticity being a contributing factor to abnormal flexor synergy. Abnormal flexor synergy arises from various factors, including motor paralysis, muscle weakness, contracture, and spasticity [32]. However, spasticity is a velocity-dependent muscle tone disturbance, while abnormal synergy involves coordinated motor disturbance, making these two phenomena distinct. Therefore, the observed correlation between the abnormal flexor synergy index and MAS was likely modest. The significant correlation with the upper limb distal scores (FMA-UE B and C, and MAS PIP flexor) may be related to abnormal upper limb proximal-distal interaction. The proximal kinematics of stroke survivors are influenced by finger function [23]. Importantly, the abnormal flexor synergy index showed a moderate positive correlation with the FMA-UE A score (a measure of proximal motor function including synergy), suggesting that the developed measure captures abnormal flexor synergy in the proximal upper limb. Hence, our findings confirm the concurrent validity of these scales.

Responsiveness

The FMA-UE A score and abnormal flexor synergy index showed good responsiveness. The FMA-UE has demonstrated high responsiveness in patients with chronic stroke [33], which aligns with our findings. In contrast, a systematic review and meta-analysis of kinematic assessments in patients with stroke reported low responsiveness [34]. Nonetheless, our developed kinematic indicator was highly responsive. This difference may be because our index captured abnormal flexor synergy, including various aspects such as motor paralysis, spasticity, and abnormal synergies of the hemiplegic upper limb.

Clinical implication

Abnormal flexor synergy index provides a quantitative and simplified assessment of upper extremity motor function. The European evidence-based recommendations for clinical assessment of the upper limb in neurorehabilitation (CAULIN) recommend including kinematic assessments alongside general upper extremity functional assessments [35]. Kinematic assessments can detect subtle changes and provide valuable information for individualized treatment planning and evaluation [36], aligning with this index. An increase in the abnormal flexor synergy index, even with the same shoulder flexion angle, implies an expanded reaching range and a deviation from the flexion synergy pattern. In the future, the optimal reaching range can be calculated using this index. Notably, our method can easily assess abnormal flexor synergy. Although kinematic assessments are increasingly used in research, no quantitative method for assessing abnormal flexor synergy has been established. Recent research using depth sensor cameras has mainly focused on interventions combined with VR technology [37], home-based applications [38], and alternatives to existing assessments [39]. While motion analysis has been conducted, it remains limited to calculating movement time, transition, and range of motion [40]. Furthermore, they are not yet widely applied in clinical practice [35] owing to their complexity and lack of user-friendliness [41]. By contrast, our measurement of the abnormal flexor synergy index took only a few seconds, making it suitable for clinical settings. Future studies should investigate its efficacy in larger cohorts and clinical trials.

Limitations

The present study has several limitations. First, the population is unbalanced due to selection bias attributable to its retrospective design. The severity of upper limb paralysis among participants was unevenly distributed. According to the FMA-UE total score, ≤ 19 points indicated severe, 20–47 points indicated moderate, and ≥48 points indicated mild impairment [42]. The classifications of participants in this study were as follows: 32 (31.1%)

severe, 61 (59.2%) moderate, and 10 (9.7%) mild in the validity analysis, and 10 (58.8%) severe, 5 (29.4%) moderate, and 2 (11.8%) mild in the responsiveness analysis. Therefore, the developed indicator may not be suitable for patients with mild upper extremity paralysis. However, these results are clinically relevant because abnormal synergy is more common in patients with severe to moderate upper extremity paralysis. Thus, this indicator could be a new measure for assessing patients with severe to moderate upper extremity paralysis. Second, the clinical data collected only included FMA-UE and MAS, leaving it unclear whether participants had cognitive or higher brain function. However, all participants were chronic stroke survivors living independently at home, a population generally at low risk for significant cognitive impairment or higher brain dysfunction. Third, MAS reliability and validity reporting was inconsistent. While some studies indicate insufficient reliability and validity of the MAS [43], others have shown its reliability [44, 45] and validity [46, 47], showing an inconsistent trend. Nevertheless, the MAS remains the most commonly used spasticity assessment tool in clinical settings, and many studies have investigated the correlation between the developed indicators and the MAS, making its use in this analysis reasonable. Furthermore, we did not investigate reliability in this study, as it depends on the device used to capture the three-dimensional coordinate data. However, the reliability of using Kinect for patients with stroke has already been demonstrated [29], ensuring the reliability of the data in this study. Therefore, the developed measure is expected to be highly reliable.

Conclusion

The assessment of abnormal flexor synergy using the newly developed index demonstrated better validity and responsiveness. The results of the present study support the use of this index to quantitatively measure upper extremity function in patients with stroke.

Abbreviations

FMA-UE	Fugl–Meyer Assessment of the Upper Extremity
MAS	Modified Ashworth Scale
MP	Metacarpophalangeal
PIP	Proximal interphalangeal
SD	Standard deviation
SRM	Standardized response mean

Supplementary Information

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Supplementary Material 1

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Not applicable.

Author contributions

DI developed the kinematic analysis methods, conducted the kinematic analysis, and wrote the main manuscript. MK assisted in developing the kinematic analysis methods, supervised the entire study, and revised the manuscript. YH contributed to the development of the kinematic analysis and participated in data analysis. TK and YY assisted with data collection. RT provided consultations on the statistical analysis. TT supervised the entire study and revised the manuscript. All authors read and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki and was reviewed and approved by the Ethics Committee of Keio University (Approval number: 20231079). The opt-out method was applied to obtain informed consent.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Rehabilitation Medicine, Keio University School of Medicine, 35 Shinanomachi, Shinjuku-ku, Tokyo 160-8582, Japan
[2]Clinical and Translational Research Center, Keio University Hospital, Tokyo, Japan

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