Highlights

High correlations were found between the TIS and the CoP excursions.

Within sessions, all CoP outcomes showed high reliability.

Between sessions, all CoP outcomes showed high reliability, except for sway velocity.

Validity and variability of center of pressure measures to quantify trunk control in stroke patients during quiet sitting and reaching tasks

Olivia Bernadette Näf [a,b,] , Christoph Michael Bauer [a*], Christian Zange [c],
Fabian Marcel Rast [a]

[a] ZHAW, Zurich University of Applied Sciences, School of Health Professions, Institute of Physiotherapy, Winterthur, Switzerland
[b] Department of Physiotherapy, Rehabilitation Center Wald, Zurich, Switzerland
[c] HELIOS Clinic Schloss Pulsnitz, Grossnaundorf, Germany

[*]Corresponding Author: Zurich University of Applied Sciences
School of Health Professions
Institute of Physiotherapy
Technikumstrasse 71
8400 Winterthur
Switzerland
+41 58 934 64 49
Christoph.bauer@zhaw.ch

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Abstract

Background:

In the immediate period following stroke, sitting balance is one of the most important predictors of functional recovery at discharge after rehabilitation. Thus, sitting balance determines the content of the early phase of stroke rehabilitation and an appropriate measurement tool is important.

Research Question:

The aim of this study is to investigate the concurrent validity of center of pressure (CoP) excursions of patients seated on a force plate, as well as to examine the daily variability of trunk control after stroke.

Methods:

Twenty stroke patients at an inpatient rehabilitation clinic underwent two assessment sessions, on average eight hours apart. Each session comprised two trials: quiet sitting for 30 seconds; extended reaching in forward, backward, left and right directions. The Trunk Impairment Scale (TIS) was measured during the first session. CoP excursions were measured to determine the outcomes of sway area and sway velocity during stable sitting and the maximal excursions in frontal and sagittal planes during the reaching tasks.

Results:

High Spearman's correlations (0.72, 0.79) were found between the TIS and the frontal and sagittal excursions. However, only low correlations between the TIS and the sway area and sway velocity were observed. Within sessions, all CoP outcomes showed high ICCs (0.73-1.00). Between sessions, high ICCs (0.86-0.93) were found except for sway velocity (ICC 0.51). Sway velocity increased significantly between sessions.

Significance:

Frontal and sagittal CoP excursions during reaching tasks appear to be valid measurement parameters to evaluate trunk control in patients after stroke. Only small variability was observed and no significant differences between consecutive days.

Keywords: Center of pressure; Force platform; Sitting balance; Trunk control; Stroke

Introduction

In the immediate period following stroke, sitting balance is one of the most important predictors of functional ability at discharge after rehabilitation [1]. This could be because unsupported sitting requires postural stability of the trunk, which is also a precondition of many other daily activities, e.g. getting up from a chair, standing, walking, reaching, bending or resisting any perturbation [2]. Postural stability is defined as the ability to maintain equilibrium by keeping or returning the center of body mass over its base of support [3]. Past research on sitting balance after stroke has generally used global clinical measurement tools, e.g. the Trunk Control Test (TCT) [4, 5], the Trunk Impairment Scale (TIS) [6], the Postural Assessment Scale for Stroke Patients (PASS) [7] and the Fugl-Meyer Test [8]. Although these tools are able to evaluate major impairments of the trunk, they have significant limitations. The outcomes of these assessments depend on experience and training of the examiner [9] and provide only ordinal scaled data. In addition, they are unable to quantify postural behavior during undisturbed sitting with precision and without a ceiling effect [10, 11]. Optoelectronic measurement systems would overcome these limitations and are recognized reference-standards for non-invasive analysis of trunk movement within research settings [12]. However, their application in daily clinical practice is limited by their high cost, required installation space, and time-consuming data capture, analysis and processing. Alternatives such as inertial measurement unit systems may be prone to local magnetic field disturbances [13]. These factors limit the analysis to some standard procedures, which cannot be extended to clinics [14].

Thus, objective measures of postural control, such as force plates, have been used to record continuous and interval scaled outcome data through measuring center of pressure (CoP) excursions [15-20]. However, few studies have used force plates to evaluate sitting balance in stroke patients [2, 9, 21]. The daily variability of patients' trunk control after stroke has not yet been examined, to the best of our knowledge. This daily fluctuation in trunk control can be a debilitating aspect of stroke rehabilitation and influence the content of rehabilitation planning.

Whether CoP excursions represent a clinically meaningful measure of trunk control during quiet sitting (sway area, sway velocity) or during seated reaching tasks (sagittal and frontal excursions) remains uncertain.

This study focuses therefore on trunk control and measures the excursions of the CoP during quiet sitting and seated reaching tasks. To evaluate whether these measures are valid in determining trunk control, a comparison with the TIS is also made. The TIS is a comprehensive tool to measure motor impairment of the trunk after stroke [6] and has shown an excellent overall test-retest (Intraclass correlation coefficient (ICC)=0.96) and interrater reliability (ICC=0.99), as well as a high correlation with the Barthel Index (Spearman's rank correlation coefficient (r_s=0.86)) and the TCT (r_s=0.83) [6]. The Barthel Index evaluates a patient's state of independence [22] and the TCT assesses the motor impairment of the trunk [5]. However, the TIS does not record objective, continuous, and interval scaled data on quiet sitting or reaching and shows a ceiling effect when measuring static sitting balance [11]. Likewise, it can only be partially recommended to measure changes over time [6]. Therefore, the study has two main aims: to investigate the concurrent validity of CoP excursions in measuring trunk control in stroke patients during seated tasks and to examine the daily variability in trunk control of stroke patients.

Methods

Participants

Twenty participants (mean age 75 ± 10 years) meeting the criteria in Table 1 were included in this study. Participation was, on average, 35 ± 23 days post stroke and the mean interval between sessions was 8 ± 7 hours. Based on an expected reliability coefficient of 0.8, a significance level of 0.05 and power of 0.8, a sample size of 20 participants was required [23]. All participants gave their oral and written informed consent prior to data collection. The study was approved by the local ethics committee (KEK Nr. 2016-00885) and conducted according to the Declaration of Helsinki [24].

Testing procedure

CoP excursion was measured using two force plates (SPS-Kraftmessplatten MLD Station Evo 5, SPSportdiagnosegeräte GmbH, Trins, Austria) and a sampling rate of 1000 Hz. A wooden board, on which the subjects sat, was placed on top of the force plates to cover the small gap between the force plates and, therefore, to enable comfortable sitting. Only the corners of this board were in contact with the force plates at predetermined locations that allowed a correct estimation of the CoP excursion. The force plates were positioned on a rigid table that could be electrically adjusted in height. To calibrate the force plates for each patients' measurement session, all forces were set to zero during a reference measure (wooden board without patient, average between pre and post measures of each session). The patients performed three tasks in fixed order: Quiet sitting, reaching in frontal plane, and reaching in sagittal plane. Patients were instructed to sit on the wooden board as quietly as possible for 30 seconds without back support, feet not touching the ground and hands placed on the abdomen. Following this, they were asked to sit and reach out as far as possible to the front and back (sagittal plane) and to the left and right (frontal plane), at their own preferred speed (Figure 1). The feet were not allowed to touch the ground to avoid balance reactions using the lower extremities. A test trial of the reaching task was undertaken in advance to ensure that the instructions were clear. Each of the three tasks was executed immediately after the test trial. One experienced physiotherapist visually judged the correct task execution, focusing on the correct movement direction. If a patient executed a task incorrectly, the instruction and the task were repeated. This whole test procedure (2x3 tasks) was repeated within four to thirty hours. At the first measurement session, an experienced physiotherapist also scored the TIS [6] to judge the trunk impairment of the stroke patients.

Signal processing

Prior to calculating the outcome variables, the signals of the CoP were filtered by a fourth-order, zero-phase, low-pass, Butterworth filter. To establish an optimal cut-off frequency (f_c), the signals were filtered with 300 different f_c, ranging from one to 300 Hz. Then, a random-

effects model with three fully crossed random effects (participants, repetition and day) and their interactions was fitted for each outcome variable (see section "Study outcomes") and f_c. The optimal f_c was established by maximizing the R-squared (R^2) of the random-effects models. A detailed description of this procedure is provided elsewhere [25]. For sway area, the signal was additionally divided into a varying number of sections ($n_{section}$), ranging from one to four (1x30 s, 2x15 s, 3x10 s and 4x7.5 s). Random-effects models were then calculated for each combination of f_c and $n_{section}$. Again, the optimal combination was established by maximizing R^2. This procedure revealed an optimal f_c of 16 Hz for frontal and sagittal excursion, 33 Hz for sway velocity and 288 Hz for sway area with dividing the whole trial into two sections. All calculations were made with MATLAB (MathWorks, USA). Labview (National Instruments, USA) was used to record data and provide the visual representation.

Study outcomes

The following outcomes were selected on the basis that they are commonly computed CoP measures [26].

Quiet sitting:

Sway velocity (mm/s):

Sway velocity was defined as the average velocity of CoP and was calculated as the total CoP path length over the time of the trial (30 seconds).

Sway area (mm^2):

The trial was divided into two sections (2 x 15 seconds). The sway area was then computed separately for each section by drawing a 95% confidence ellipse for a set of 2D normally distributed data samples [27] and calculating the area of that ellipse. The two sway area outcomes were averaged to obtain the mean measured sway area for each trial.

Reaching in frontal and sagittal plane:

Frontal and sagittal excursions (mm):

The ability to reach to the furthest extension in the frontal and sagittal planes is quantified by

the difference between the maximal and minimal CoP excursion in the mediolateral and anteroposterior directions, respectively. The total excursion was calculated by summing the excursions of both tasks.

TIS (number of points):

The TIS is a rating sheet that is divided into three sections: static (three items), dynamic (ten items) and co-ordination (four items). Each item is rated between zero to three points, depending on the task. An overall maximum of 23 points is achievable. The greater the number of points, the better the trunk control of the patient [6]. The sub-scores of the static and dynamic sections and the total score were calculated for each patient. The TIS is a well-established test and benchmark for postural control against which this novel procedure was tested. However, the testing procedure does not replicate the TIS but was developed to measure trunk control while minimizing the influence of the functional status of the patients' lower extremities.

Statistical Analysis

Means of the two repetitions per session were calculated for all CoP outcomes (sway velocity, sway area, frontal excursion, sagittal excursion, and total excursion) for each subject. These means enabled determination of the ICCs (3,1), their 95% confidence intervals (CI) [28] and differences between sessions. Additionally, all outcomes and computed means were tested for normal distribution, using the Shapiro-Wilk method. Where the data was not normally distributed ($p<0.1$) [29], a logarithmic transformation was applied.

Concurrent Validity

To assess concurrent validity, r_s and their 95% CI were used to determine correlations between the mean of the first session CoP outcomes and the score of the TIS (total, static and dynamic scores). A correlation between two tests on the same attribute should fall within the midrange of 0.4-0.8 [30]. A lower correlation suggests either that the reliability of one of the tests is unacceptably low, or that they are measuring different phenomena. A greater correlation would suggest that both tests might be interchangeable [30].

Variability

The differences within sessions, (first session: repetition two – repetition one; second session: repetition four – repetition three) and between sessions (mean second session – mean first session) were calculated. The minimal accepted level of the ICC was set at 0.7 [31]. Central tendencies of all CoP outcomes were compared and tested for statistically significant differences within sessions and between sessions, using the Wilcoxon-Signed-Rank-Test. All data was collected and analyzed using IBM-SPSS Statistics Version 24 (IBM, USA). The significance level was set at $p<0.05$.

Results

All patients completed the test procedure on both measurement sessions. Thus, there were no missing data. The median, lower, and upper quartile outcomes of trials one to four, as well as the mean results from session one and session two, are presented in Table 2.

Concurrent Validity

The Spearman's rank correlation coefficients and 95% CI between the TIS and the CoP outcomes are illustrated in Table 3. Generally, stronger correlations between the TIS and the frontal and sagittal CoP excursions (r_s=0.57-0.80) were seen than between the correlations of the TIS and the CoP sway area or sway velocity (r_s=-0.42-0.18).

Variability

Because not all differences were normally distributed, the median, lower and upper quartiles of the differences within sessions and between sessions are listed in Table 2. The only significant difference, according to the Wilcoxon-Signed-Rank-Test (p=0.03), was found between the mean sway velocities of sessions one and two. Within session and between session ICCs and 95% CI are presented in Table 4. All ICCs and lower values of the 95% CI of the frontal and sagittal CoP excursions were above 0.7. Slightly lower ICCs (0.73-0.86) and unacceptably low values of the 95% CI (0.43-0.68) were shown for the sway area. Sway velocity revealed excellent within session ICCs (95% CI of 0.97-1.00) and an unacceptable between session ICC of 0.51 (95% CI of 0.10-0.87).

Discussion

The purpose of this study was to investigate the concurrent validity of commonly used CoP outcomes (sway velocity, sway area, frontal excursion, sagittal excursion and total excursion) designed to measure trunk control of stroke patients in sitting and to examine the daily variability of trunk control.

To evaluate the concurrent validity of the selected trunk control CoP outcomes, they were compared with the TIS. Most of the Spearman's rank correlations between the CoP outcomes and the TIS fell into the midrange of 0.4-0.8. The highest Spearman's rank correlation was found between the total points of the TIS and the total excursion in the combined sagittal and frontal planes. This is not surprising because the maximal excursion in both planes combines two tasks, reflecting trunk control in four directions: forward, backward, left and right. Interestingly, the total number of points of the TIS mostly showed stronger correlations with the CoP measures than only parts of the TIS. This might be due to the isolated interpretation of the subscales of the TIS. It was expected that the dynamic part of the TIS would show stronger correlations with the frontal and sagittal excursions and that the static part of the TIS would show stronger correlations with the quiet sitting parameters. The negative correlation between the TIS and the sway area was as expected, with more movement on the force plate indicating less trunk control [2, 9]. The low correlation between TIS and sway area, as well as sway velocity, could be because they are not measuring the same phenomena. It is conceivable that a rating sheet is unable to quantify the small movements of quiet sitting, as few parameters can be quantified during quiet sitting. This could explain the low correlation between TIS, and sway velocity respectively sway area. For this situation, a force plate could be a useful tool because it measures continuous data, recording even small changes, compared to a rating sheet that has a maximum of 23 achievable points. However, the relationship between sway velocity and area with trunk control is rather complex and requires further research. It seems reasonable that a small sway area corresponds to increased trunk control, since the probability of the CoP remaining within the base of support is increased, which is the definition of postural stability [3]. A high sway velocity could be interpreted either

as increased trunk control, due to the many functional adaptations required to react to perturbations, or as decreased trunk control due to the fast and large excursions of the CoP. However, also a non-linear, perhaps U-shaped, relationship between CoP outcomes and trunk control is possible where both low and high values of CoP outcomes could indicate different forms of trunk control impairment [32]. This hypothesis is supported by studies from other patient populations, such as Parkinsons disease, elderly fallers, and non-specific low back pain, and warrants further investigation in stroke patients [32-35].

To determine daily variability, differences and ICCs were examined. Differences were found within both sessions one and two, even though the trials followed straight after each other. A negative sign in the median differences within sessions means that the central tendency of the second trial was lower than the first. Hence, the negative median difference of the frontal excursion within session two could be due to, for example, tiredness. On the other hand, a positive value of the median difference could be due to learning. The opposite interpretation can be applied to the sway area because the larger the area, the less the trunk control [9]. The outcomes, however, showed no significant differences and, therefore, might be due to coincidence. The only significant difference was shown between the median sway velocities of sessions one and two (Table 2). Between session differences are most likely due to the varying state of health of the patient, or due to measurement error. Since the time interval between the sessions was short, a learning effect can be assumed and is to be expected within sessions. Unlikely, but also possible, is an improvement occurrence in sitting balance.

All ICCs of the sway area showed values of 95% CI below 0.7. This is not surprising if we look at the distribution of the outcomes. The sway area, as well as the sway velocity, showed smaller interquartile ranges (upper quartile – lower quartile) compared to the frontal and sagittal excursions. The lower the between-participant variability, the lower are the ICCs [36]. The generally lower ICCs between sessions, compared with within sessions, was not unexpected. The larger time intervals between the sessions can lead to a difference in the state of health, or, less likely, an improvement in sitting balance over time. This is especially striking in sway

velocity. Sway velocity could possibly be more sensitive to day-to-day fluctuations, an early indicator of improvements in sitting balance, or simply a sensitive outcome to signal noise and small changes in the measurement setup. The distinction between measurement error and functional improvements should be investigated in a responsiveness study. Previous studies have shown comparable results. In able-bodied children, Lacoste et al. measured mean CoP excursion during quiet sitting of 7.2 mm in sagittal plane and 5.8 mm in frontal plane, which would be a comparable calculated area of about 41.8 mm^2 [37]. ICCs of 0.61 (CI=0.35-0.83) and 0.50 (CI=0.16-0.73) were observed in their study. These can be considered as lower correlations compared to the identified ICCs and CI of the sway area in this study [37]. Their reaching task outcomes cannot be compared to our study because of differences in execution. Nichols et al. examined the ICCs of comparable tasks in stroke patients, as well as healthy subjects, but the center of force data was expressed as a percent change in body weight distribution [38]. Through measuring three sessions of two repetitions, with each session two weeks apart, they showed different within session ICCs for each session. Patients after stroke showed comparable within session ICCs in frontal excursion (0.76-0.95) and lower ones in reaching forward (0.82, 0.53, 0.71) compared to the ICCs of the sagittal excursion (0.95, 0.92). In the steady sitting position, the within session ICCs varied considerably between each session (0.30, 0.75, 0.43) and are mostly lower than the within session ICC of the static CoP outcomes. Healthy subjects showed generally high within session ICCs (0.86-0.96), which is surprising due to lower between-participant variability in the measurements [38]. It appears that the CoP excursions in the sagittal and frontal planes, as well as the sway velocity and sway area, show better correlations and, therefore, might be a more reliable outcome measure than the percent change in body weight. Future studies should address properties such as the minimal clinically important difference of CoP measures.

Some limitations may have biased our results. Firstly, the time interval between the measurement sessions differed allowing activities between sessions to vary between patients. In consequence, different states of health are to be expected. Secondly, we did not have

information on previous therapy that patients had received or the communality of the tasks. Patients who had never previously executed reaching tasks could have shown a larger learning effect between the repetitions, resulting in lower ICCs and bigger differences. The third limitation of this study is the limited external validity due to the inclusion and exclusion criteria. Only patients who were able to understand that they were participating in a research study and could sign a consent form were included. Many stroke patients have high cognitive limitations, and cannot consequently be included in the study; therefore, external validity is limited. Choosing an appropriate filtering technique is a compromise between loss of information and allowing noise through. We could possibly have missed small fragmentations of movement that might have influenced the validity and variability. Future studies should address options that might conserve such information. The test schedule matched the patients' rehabilitation program, resulting in long between measurement intervals, excluding a daily interval of examination in some patients. Therefore, improvements of postural control might have influenced the results. The patients' rehabilitation program had to continue as planned, so it was not possible to schedule both tests at the same daytime. Consequently, intersession changes due to tiredness might have influenced the results.

Conclusion

The frontal and sagittal excursions during reaching tasks measured by a force plate seem to be valid parameters for the evaluation of trunk control in patients after stroke. Low variability between measurements was found (no significant differences and high ICC within sessions and between sessions). Although sway velocity and sway area generally showed high ICCs, only low, or no, correlation with the TIS was seen. Thus, validity was not confirmed. Further research is required to determine whether sway area and sway velocity are valid outcomes for measuring steady sitting. Comparison with a healthy control group would be interesting and responsiveness should be evaluated.

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Frontal excursion Sagittal excursion

Figure 1. Frontal and sagittal excursions on the force platform

Table 1.

In- and exclusion criteria. The aim of these criteria was to include only those patients who were able to perform the tasks on the force platform and understand the instructions of the TIS, but who were nevertheless affected in their balance capacity.

Inclusion Criteria	Exclusion Criteria
The patient was hospitalized at a rehabilitation center	The patient was younger than 55 years of age
The patient was unable to walk, or walk only with the assistance of a walker , lift walker or walking frame	The patient was not capable of understanding or executing the testing procedure
The patient understood instructions and could execute them adequately	The patient was more than three months post stroke
	The patient was unable to sit for 30 seconds without back support and ground contact

Table 2.

Descriptive statistics: Median, lower (Q1) and upper quartile (Q3) for all CoP outcomes of trial 1-4, session 1 (mean of trial 1 and 2) and session 2 (mean of trial 3 and 4), differences (Ddiff.) within session 1 (mean trial 2 - mean trial 1), differences within session 2 (mean trial 4 – mean trial 3), and between session differences (mean session 2 – mean session 1). Significant differences between trials and between sessions according to Wilcoxon-Signed-Rank-Test are marked.

	Quiet sitting		Reaching in frontal and sagittal plane		
	Sway velocity (mm/s)	Sway area (mm^2)	Frontal excursion (mm)	Sagittal excursion (mm)	Total excursion (mm)
	Median (Q1, Q3)	Median (Q1, Q3)	Median (Q1, Q3)	Median (Q1, Q3)	Median (Q1, Q3)
Trial 1	67 (53, 76)	48 (28, 84)	160 (111, 219)	183 (145, 266)	340 (262, 437)
Trial 2	67 (53, 77)	43 (21, 72)	167 (110, 218)	198 (138, 237)	322 (256, 449)
Trial 3	79 (63, 106)	46 (29, 73)	167 (134, 220)	180 (158, 279)	354 (297, 457)
Trial 4	80 (62, 110)	36 (24, 59)	157 (117, 215)	196 (165, 269)	364 (271, 441)
Mean Session 1	67 (53, 77)	47 (26, 82)	166 (112, 217)	185 (143, 237)	323 (253, 445)
Mean Session 2	79 (63, 108)	43 (28, 71)	165 (121, 217)	186 (164, 275)	355 (286, 442)
Diff. session 1	0 (-1, 1)	-8 (-16, 6.)	0 (-19, 9)	8 (-9, 26)	5 (-18, 27)
Diff. session 2	2 (-2, 4)	-4 (-13, 2)	-8 (-24, 5)	1 (-11, 12)	-3 (-31, 12)
Between session diff.	6 [a] (-2, 40)	2 (-7, 13)	2 (-20, 23)	-5 (-22, 6)	12 (-35, 36)

[a] Wilcoxon-Signed-Rank-Test: significant difference between session $p<0.5$

Table 3.

Results of concurrent validity: Spearman's rank correlation coefficient (r_s) and 95% confidence interval (CI) between the Trunk Impairment Scale (TIS) (total points, points of the static part, points of the dynamic part) and the different CoP outcomes (sway velocity, sway area, frontal excursion, sagittal excursion, total excursion).

	Quiet sitting		Reaching in frontal and sagittal plane		
	Sway velocity (mm^2)	Sway area (mm/s)	Frontal Excursion (mm)	Sagittal Excursion (mm)	Total Excursion (mm)
	r_s (95% CI)	r_s (95% CI)	r_s (95% CI)	r_s (95% CI)	r_s (95% CI)
TIS (Total points)	0.13 (-0.32-0.53)	-0.42 (-0.72-0.03)	0.79 (0.52-0.91)	0.72 (0.39-0.88)	0.80 (0.53-0.92)
TIS (Static points)	0.18 (-0.28-0.57)	-0.30 (-0.65-0.16)	0.57 (0.17-0.80)	0.66 (0.29-0.85)	0.62 (0.22-0.83)
TIS (Dynamic points)	0.12 (-0.33-0.52)	-0.36 (-0.68-0.10)	0.71 (0.38-0.87)	0.62 (0.22-0.83)	0.70 (0.35-0.87)

Table 4.

Intraclass correlation coefficient (ICC) and 95% confidence interval (CI) within sessions (between trials 1 and 2 respectively trials 3 and 4) and between sessions (between mean of session 1 and mean of session 2) of all variables of CoP excursion

	Within session 1 ICC (95% CI)	Within session 2 ICC (95% CI)	Between sessions ICC (95% CI)
Quiet sitting			
Sway velocity (mm/s)	1.00 (0.99-1.00)	0.99 (0.97-1.00)	0.51 (0.10-0.87)
Sway area (mm^2)	0.81 (0.59-0.92)	0.73 (0.43-0.88)	0.86 (0.68-0.94)
Reaching in frontal and sagittal plane			
Frontal excursion (mm)	0.95 (0.88-0.98)	0.92 (0.81-0.97)	0.88 (0.71-0.95)
Sagittal excursion (mm)	0.95 (0.88-0.98)	0.98 (0.95-0.99)	0.93 (0.82-0.97)

Conflict of interests

None.

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