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Paper

A Video-Based Gait Disturbance Assessment Tool for Diagnosing Idiopathic Normal Pressure Hydrocephalus

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Gait is an important factor in the diagnosis of idiopathic normal pressure hydrocephalus. However, except for walking speed tests, existing diagnosis methods only assess gait qualitatively. This study proposes a quantitative and multifaceted method to assess gait disturbance via video-based analysis. We captured videos of patients walking from the front to assess four gait disturbance qualities: lateral sway, petit-pas gait, wide-base gait, and duck-footed walking. These features were selected from the Gait Status Scale-Revised, an existing scale of idiopathic normal pressure hydrocephalus gait disturbance. We confirmed that our assessments of all selected items, except for lateral sway, were consistent with physician assessment. We also used the P-value of the gait disturbance scores before and after lumbar puncture to assess the outcome of the cerebrospinal fluid tap test, and confirmed that tap-positive and tap-negative patients were successfully separated by a threshold of $P = 0.01$. © 2019 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

Keywords: normal pressure hydrocephalus; gait; computer-aided diagnosis; computer vision

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1. Introduction

Normal pressure hydrocephalus (NPH) is a syndrome first described by Hakim and Adams [1] that is characterized by the classic clinical triad of gait disturbance, cognitive dysfunction, and urinary symptoms. NPH is further classified into secondary and idiopathic NPH (iNPH). iNPH develops without an identifiable cause, and occurs in approximately 1% of older adults [2,3].

According to the Japanese guidelines for the management of iNPH [4], iNPH is classified into three diagnostic levels: preoperatively 'possible', 'probable', and postoperatively 'definite'. The diagnostic flow is provided as follows:

Step 1: Patients with at least one of the symptoms of dementia, gait disturbance, and urinary incontinence (known as the clinical triad) [5,6], and who meet other criteria, are diagnosed as possible iNPH.

Step 2: The possible iNPH patients who meet the criteria of a cerebrospinal fluid (CSF) examination, and who have one investigational feature obtained by morphologic brain imaging [7,8] or a CSF tap test [9,10], are diagnosed as probable iNPH. The CSF tap test is judged by the improvement of the clinical triad, particularly the gait disturbance [11,12]. More specifically, a patient undergoes fixed-distance walking tests such as the Timed Up & Go (TUG) test [13] before and after the lumbar puncture of the CSF tap test. Thereafter, the patient is labeled as tap-positive if they gain >10% improvement in walking time as an objective (quantitative) criterion, or improvement in gait disturbances through visual inspection by a physician as subjective (qualitative) criterion, otherwise, the patient is labeled as tap-negative. The tap-positive patients are then diagnosed as probable iNPH.

Step 3: A surgical procedure (i.e., a shunt surgery) is indicated for the probable iNPH patients, and the patients with improved postoperative symptoms are diagnosed as definite iNPH.

In the present study, we focused on the CSF tap test (Step 2). Because it is difficult to correctly judge all patients using a single objective criterion (i.e., the walking time), additional criteria are required. The criteria associated with qualitative gait disturbance assessment through visual inspection by a physician are useful; however, they are strongly dependent on the subjectivity and degree of proficiency of the individual physicians. Indeed, the physician requires considerable experience to make a correct judgment through visual inspection. Thus, it is necessary to develop a quantitative method to assess gait disturbances from multiple aspects to improve the accuracy of diagnosis.

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Other studies assessing gait disturbance to diagnose iNPH have also used qualitative visual inspection-based methods including the dynamic gait index [14], the Tinetti performance-oriented mobility assessment [15], or a customized criterion [16,17]. Although there are several studies that discuss the quantitative assessment of gait disturbances in iNPH, the techniques require special equipment such as accelerometers [18], footswitches [19,20], knee goniometers [19], and motion capture systems [20], which are unlikely to be available for routine clinical use.

By contrast, video-based gait disturbance assessment is promising for routine clinical use as patients do not need to wear accelerometers or goniometers, and setup of a commercially available digital video camera is easier than that for aligned footswitches. Indeed, the efficacy of video-based gait analysis is well established in the fields of computer vision, pattern recognition, and biometrics. In particular, holistic silhouette-based gait representation [21,22] is widely used in video-based gait analysis, with numerous applications including human identification, forensics, gait personality measurement, gender classification, and age estimation [23–28].

The abovementioned holistic silhouette-based gait representations are, however, not necessarily effective for medical/health applications and hence we often require more directly interpretable gait features (e.g., stride [29], sudden motion variation [30], etc.) in the medical/health applications. The existing methods in medical/health field [29–31] usually extract the directly interpretable gait features from a side-view image or multiview images including side-view images. Since it requires a relatively large space to capture a walking image sequence from the side view, application scenes are limited for the methods, which require the side-view images. Considering that walking tests are often conducted at narrow corridors in the hospital in clinical practice, it is desirable to extract the gait features from frontal view to save space.

The aim of the present study is to quantitatively assess the gait disturbance of iNPH patients using video-based gait analysis (without the requirement for any special equipment), and to validate its efficacy for judgment of the CSF tap test. More specifically, we select four gait features from the gait status scale-revised (GSSR), which is used in subjective assessment by physicians, and to develop a method to quantitatively assess the four gait features to judge the CSF tap test more accurately compared with that using a single quantitative criterion (i.e., the walking time).

2. Method

2.1. Patients We recruited eighteen patients (twelve women and six men) who were previously diagnosed with possible iNPH at Osaka University Hospital (Table I). CSF tap tests were performed on the patients, and a set of walking tests were performed twice daily over at least 5 days just before and after the tap tests. Patients judged as tap-positive in the tap test were indicated for shunt surgery, and another set of walking tests was performed after the surgery to verify the tap test results. Two tests were included in each set of walking tests: the 3 m TUG and the 10 m walking test (TMW). The tests are both round-trip walks, where the TUG starts from sitting on a chair, and contains the actions for standing and sitting, whereas the TMW does not. The best time scores for each of the two walking tests were taken from each set performed before and after the CSF tap test. If either or both of the best time scores of the TUG and the TMW for a patient improved by $>10\%$ after the tap test, the patient was judged as tap-positive, and vice versa. Nine patients were judged to be tap-positive in the preoperative walking tests, while the others were tap-negative. Of the tap-positive patients, two had no improvement in their walking time (defined here as speed-negative patients) in both the TUG and the TMW, and were diagnosed with tap-positive by gait improvement assessed through visual inspection by physicians. However, the results of the postoperative walking tests proved that all nine patients had definite iNPH, indicating that the tap-positive assessment of the speed-negative patients was correct.

Table I. Patient characteristics and walking test scores

No.	Gender	Age (year)	Result of tap test	$>10\%$ improvement	
				TUG	TMW
P1	Female	71	Positive	Yes	No
P2	Female	82	Positive	Yes	Yes
P3	Male	75	Positive	Yes	No
P4	Female	67	Positive	No	Yes
P5	Female	80	Positive	Yes	No
P6	Female	76	Positive	Yes	No
P7	Female	68	Positive	Yes	No
P8	Female	78	Positive	No	No
P9	Male	75	Positive	No	No
N1	Female	72	Negative	No	No
N2	Male	78	Negative	No	No
N3	Female	82	Negative	No	No
N4	Male	69	Negative	No	No
N5	Female	81	Negative	No	No
N6	Male	75	Negative	No	No
N7	Female	87	Negative	No	No
N8	Male	72	Negative	No	No
N9	Female	83	Negative	No	No

For gait disturbance analysis, we captured walking videos of the patients from the frontal view using a consumer digital video camera (Sony Corporation, Tokyo, Japan), with a resolution of 1920×1080 pixels and a frame rate of 30 frames per second. The videos included multiple trials of TUG and TMW, which were performed before and after the lumbar puncture.

2.2. Gait feature assessment

2.2.1. Gait features To select the gait features to be assessed, we referred to an existing scale of gait disturbances of iNPH, termed the GSSR [32]. GSSR is a qualitative scale that relies on visual inspection by a physician. The GSSR consists of 10 evaluation items: lateral sway, petit-pas gait, wide-base gait, duck-footed walking, shuffle, freezing of gait, festinating gait, disturbed tandem walking, postural stability, and independence of walking. The scale requires that each item of the GSSR is rated with a discrete value (e.g., 0 and 1), and the total score is then used to judge if the patient has a gait disturbance caused by iNPH. In the present study, we focused on four items (lateral sway, petit-pas gait, wide-base gait, and duck-footed walking) because the features associated with these items can be observed from frontal gait image sequences (i.e., videos) of the patient, which can be captured relatively easily during walking tests.

2.2.2. Assessment method The proposed assessment methods of the four items are described below. Figure 1 illustrates how the specific gait features were used.

Preprocessing We manually selected the stable-walking sequences for assessment from the video, beginning from the frame in which the patient moved his/her foot to take the first step, until the frame in which he/she takes a step to the change direction before the turn-back point. Because the walking distance was only 3 m in TUGs, the patients' stable-walking sections were too short for assessment. Thus, we selected all image sequences from the TMWs. To prepare for the following assessment, we first

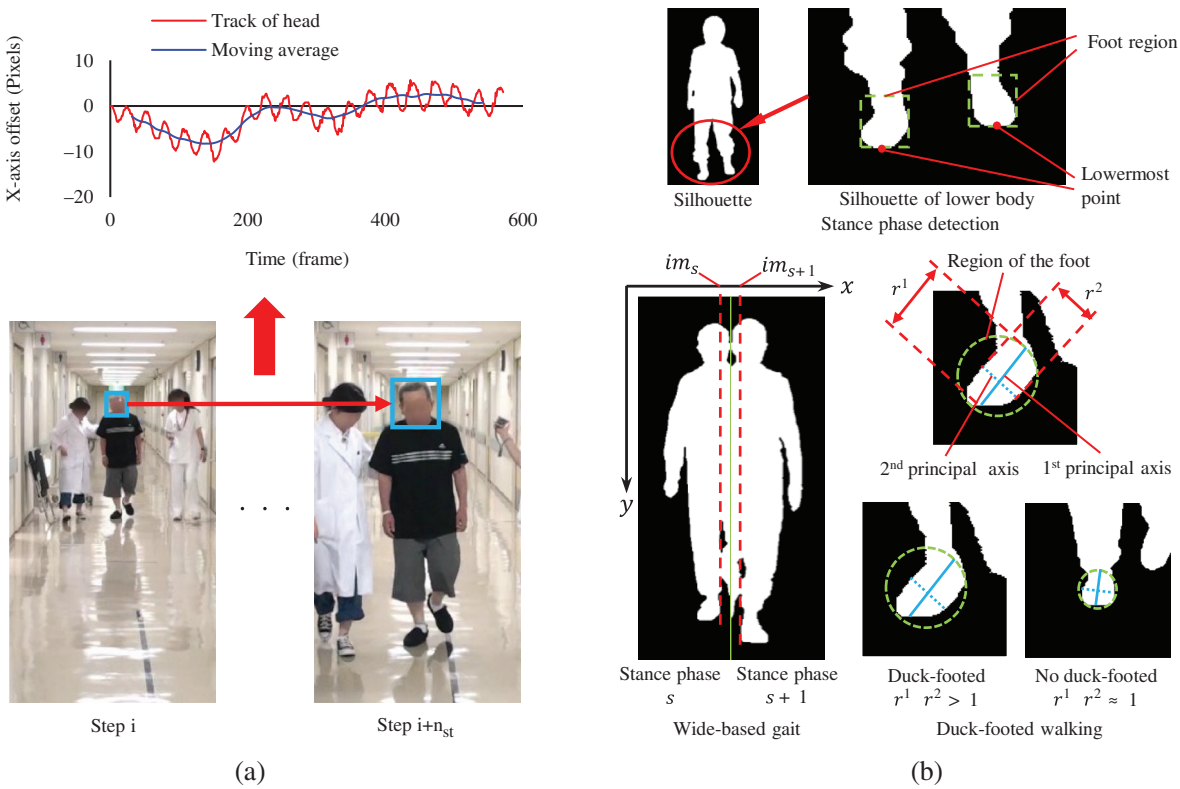

Fig. 1. Gait assessment. We assessed lateral sway and petit-pas gait by face tracking and step counting in the whole image sequences, and assessed the wide-base gait and duck-footed walking using the silhouette-based analysis in the subsequences that extracted the silhouette. In the duck-footed walking part of panel (b), we provided two silhouettes of the feet from different patients, with and without duck-footed walking. The principle axis ratio of the silhouette without duck-footed walking was close to 1, while that of the silhouette with duck-footed walking was significantly >1. (a) Face tracking and step counting; (b) assessment of wide base gait and duck−footed walking

detected the patients' faces with a commercial off-the-shelf face detector (OKAO Vision; OMRON Corporation, Kyoto, Japan), and blurred their faces for privacy protection. We then estimated the camera orientation based on the parallel lines of a corridor in the hospital, and corrected the image rotation/tilt using the camera orientation so that the image plane is perpendicular to both the ground and the wall surface. It allows us to obtain the horizontal or vertical distance of the two points by measuring the coordinates. For the silhouette-based gait analysis, we extracted the whole body silhouette of a patient. Because gait is periodic, we selected a subsequence composed of two stable gait periods with sufficient image resolution of the patient from the entire image sequence to reduce the time required for silhouette extraction. We normally chose the last two gait periods before turning around that had no step fluctuation. We extracted the silhouette using the grab-cut algorithm [33] for semiautomatic segmentation, and added manual interventions to create a higher quality silhouette. We also manually set the bounding boxes for the patients' regions throughout the whole sequence.

Lateral sway Lateral sway assesses the trunk's sway during walking. As defined by the GSSR, patients with trunk sway are given a score of 1, and patients with fluctuations in their heel strike positions are given a score of 2. In the present study, we only used the score of 1 to assess trunk sway. As shown in Fig. 1(a), we computed the trajectory of each patient's head position along a horizontal axis provided by face tracking, and subtracted the moving average of the trajectory to calculate the deviation of the head from the midline of the body. We then normalized the deviation by the patient's height (i.e., the height of the bounding box to the patient) because the amount of lateral sway is scaled by the patient's height, and computed the mean of the normalized deviation as the lateral sway score

$$q_{\mathrm{LS}} = \frac{1}{h_i}\frac{1}{n-2\lfloor p/2\rfloor}\sum_{i=\lfloor p/2\rfloor}^{n-\lfloor p/2\rfloor}(c_i-\bar{c}_i),$$

where h_i (pixel) is the height of bounding boxes (i.e., the height of a patient) at the ith frame, n (frame) is the number of frames in an image sequence, p (frame) is the gait period of patient, $\lfloor\cdot\rfloor$ is a floor function, c_i is the horizontal position of the center of patient's head at the ith frame, and $\bar{c}_i$ is a moving average of c_i with a period of p, which can be computed as,

$$\bar{c}_i = \frac{1}{p}\sum_{k=i-\lfloor p/2\rfloor}^{i-\lfloor p/2\rfloor+p-1} c_k.$$

Petit-pas gait Petit-pas gait literally means 'gait with a very small stride'. As shown in Fig. 1(a), we counted the number of steps during the walking test and calculated the stride. Because the stride is scaled by the patient's height, we normalized the stride by the height of the bounding boxes, and then defined the normalized value as the petit-pas gait score

$$q_{\mathrm{PG}} = \frac{1}{h_{\max}}\frac{L}{n_{\mathrm{st}}},$$

where $h_{\max}$ is the maximum height of bounding boxes when patient reaches the turn-back point, L is the length of the walking course, and n_{st} is the number of steps.

Wide-base gait and duck-footed walking A wide-base gait means that the lateral interval between the feet of the patient while the walking is wide. Duck-footed walking means that the

patient's large toe is oriented outwardly during the stance phase. Because both features are observable during the stance phase, we try extracting the stance phases from a silhouette sequence. For this purpose, we first locate feet search window whose bottom, left, and right coincide with the bottom, the left, and the right of the bounding box, respectively, and whose height is set in proportion to the height of the bounding box. We then divide the window by its horizontal middle point into left/right foot search subwindows, and a silhouette region inside the left/right foot search subwindow is regarded as left/right foot region. We then extract the bottom of the left/right foot region as the foot bottom points. Finally, we can estimate a phase ϕ_i (stance phase or non-stance phase) at the ith frame by analyzing the vertical movement of the foot bottom points based on the assumption that the vertical movement should be small at the stance phase as

$$\phi_i = \begin{cases} \text{Stance phase,} & \Delta y_i^b \leq \alpha \\ \text{Non-stance phase,} & \text{otherwise} \end{cases},$$

$$\Delta y_i^b = y_{i+1}^b - y_i^b,$$

where y_i^b is the vertical position of the foot bottom points, and α is a threshold to judge the phase. The threshold is automatically determined by Otsu's discriminant analysis criterion on a histogram obtained by a set of the vertical movements $\{\Delta y_i^b\}$ for each patient.

We analyzed the silhouettes of the stance phases for evidence of a wide-base gait or duck-footed walking (Fig. 1(b)).

In the assessment of wide-base gait, we calculated the horizontal distance between the innermost points of the foot silhouettes during adjacent stance phases, and normalized them by the height of bounding boxes. The mean of these normalized values was defined as the wide-base gait score

$$q_{\mathrm{WG}} = \frac{1}{n_{\mathrm{sp}}} \sum_{s=1}^{n_{\mathrm{sp}}-1} \mathrm{distance}(x_s, x_{s+1}),$$

$$\mathrm{distance}(x_s, x_{s+1}) = \begin{cases} x_s - x_{s+1}, & \text{Stance phase } s \text{ is left foot} \\ x_{s+1} - x_s, & \text{Stance phase } s+1 \text{ is left foot,} \end{cases}$$

where n_{sp} is the total number of stance phase of both feet, and x_s is the horizontal position of the innermost point of the landing foot's silhouette in the stance phase s.

In the assessment of duck-footed walking, we first extracted the foot silhouette's region by setting bounding boxes for the left/right foot that were proportional to the full-body bounding box. The proportion was predefined experimentally so that the bounding boxes can contain the left/right foot. We then computed the principal axes of the foot silhouette's region by principal component analysis during the stance phase, and assessed the length of first and second principal axes. The ratio of the length of the first and second principal axes is close to 1 when the toe is straight forward, and is larger as the toe is oriented outward. We therefore defined the sum of the ratios of the two feet as the score of duck-footed walking. The score is defined by

$$q_{\mathrm{DW}} = \sum_{f \in \{\mathrm{left,right}\}} \frac{1}{n_{\mathrm{sp}}^f} \sum_{s=1}^{n_{\mathrm{sp}}^f} \frac{r_s^{f,1}}{r_s^{f,2}},$$

where $r_s^{f,k}$ is the length of the kth principal component of the foot f's region in stance phase s, and $n_{\mathrm{SP}}{}^f$ is the number of stance phases of the foot f.

Unlike the first two features, wide-base gait and duck-footed walking are assessed from only two walking cycles where the silhouettes are extracted.

2.3. Judgment of the CSF tap test We used the four gait features (i.e., lateral sway, petit-pas gait, wide-base gait, and duck-footed walking) extracted from a gait image sequence and the walking time to improve the judgment for the CSF tap test. Because it was previously reported that the speed of turning around is important for the CSF tap tests [34,35], we also used the time for turning around at the halfway point of the TUG and the TMW, in addition to the total walking time. Specifically, we manually set the frame where the patient moved his/her foot to take the first step at the start time, and set the frame where the patient crossed the finish line at the end time, to assess the total time spent for walking. Similarly, we assessed the turning time by selecting the frame where the patient changed direction to turn at the start time, and set the frame where the patient completed the turn and took the first step to walk straight at the end time.

We used a statistical method to calculate a score for the judgment. We employed a t-test for each feature, and calculated the P-values of each assessment before and after the tap test. We then selected the minimum P-value of all the features as the judgment scores (i.e., we selected the feature with the best improvement).

3. Results

3.1. Feature assessment Assessment of the four features (i.e., lateral sway, petit-pas gait, wide-base gait, and duck-footed walking) is shown in Fig. 2. To clarify the relationship between the assessed values and the GSSR scores determined by physicians, we grouped patients by the GSSR scores and sorted them by the assessed values within each group. The assessed values of the time measurements are also shown in Fig. 3, which are used to help judging the results of the tap-test in current clinical practice.

As shown in Fig. 3, there was a significant improvement in the walking time of some tap-positive patients (e.g., patients P2, P3, and P6), while the walking time is a quantitative feature used in current clinical practice. The tap-positive patients did not always exhibit significant time improvements (e.g., patient P1), implying that the walking time alone is insufficient for accurate judgment of the tap-test. However, we noticed that patient P1 had a significant improvement in lateral sway ($P < 0.01$), while the speed-negative patients P8 and P9 had a significant improvement in lateral sway and petit-pas gait.

We also compared the assessed values obtained by our quantitative assessment method with the GSSR scores determined by the subjective physician assessments. As shown in Fig. 2, the assessed values and the GSSR scores showed a similar trend for petit-pas gait, wide-base gait, and duck-footed walking, except for a few cases. However, there were no differences in the assessed values of lateral sway between the patients with a score of 0 and those with a score of 1 or 2.

3.2. Judgment of the CSF tap test For each patient, we calculated the P-values before and after the tap-test for each gait feature and for walking time. The results are shown in Table II. The selected minimum P-value for each patient is shown in Fig. 4, which is used to judge the results of the tap test. The assessed values of the corresponding features before and after the CSF tap test are listed in Table III. The minimum P-values for the two speed-negative patients (i.e., P8 and P9) were <0.005, which supports the requirement for multifaceted assessments to improve clinical judgment by the physician.

We also found that the minimum P-values of all tap-positive patients were always less than those of all tap-negative patients. Thus, we can successfully confirm tap-positive and tap-negative patients based on the minimum P-value derived from the assessed

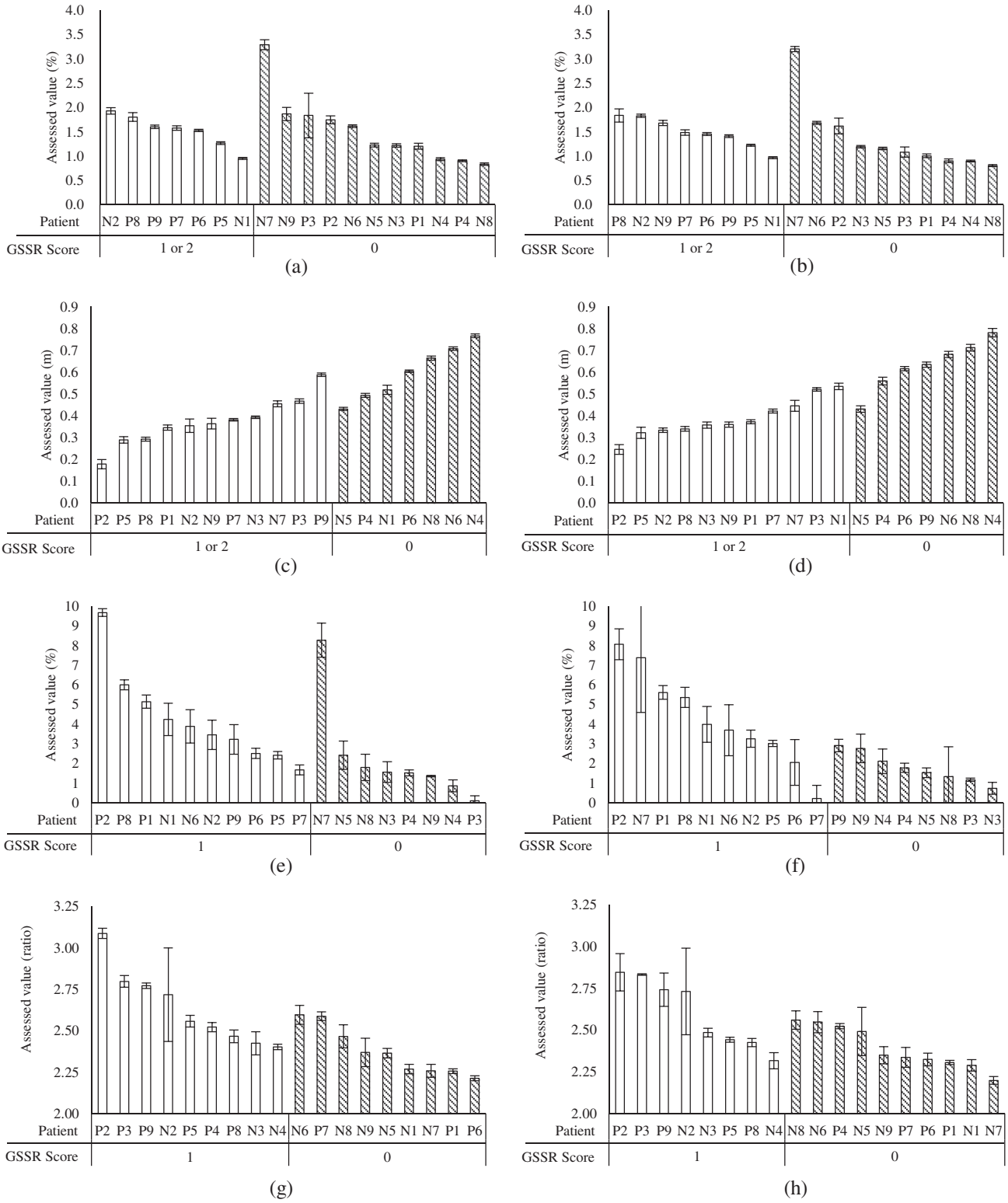

Fig. 2. The mean (±standard deviation for sample mean) of the assessed values compared with GSSR scores that are labeled by the treatment physician. For lateral sway, wide-base gait, and duck-footed walking, patients with the symptoms should have a higher value than those without symptoms, while for petit-pas gait the symptomatic patients should have a lower value. (a) Lateral sway, pre-tap; (b) lateral sway, post-tap; (c) petit-pas gait, pre-tap; (d) petit-pas gait, post-tap; (e) wide base gait, pre-tap; (f) wide base gait, post-tap; (g) duck-footed walking, pre-tap; (h) duck-footed walking, post-tap

gait disturbance features with an appropriate threshold (e.g., $P = 0.01$).

4. Discussion

We assessed the four gait disturbance features of iNPH quantitatively, and confirmed that most of the assessed values of petit-pas gait, wide-base gait, and duck-footed walking were consistent with the physicians' judgment, while the assessment of lateral sway has some discrepancies. We also used the assessed value to improve the judgment for the CSF tap test, and concluded that judgment using silhouette-based gait assessment is more effective than existing quantitative judgment methods, which only use the recorded walking time.

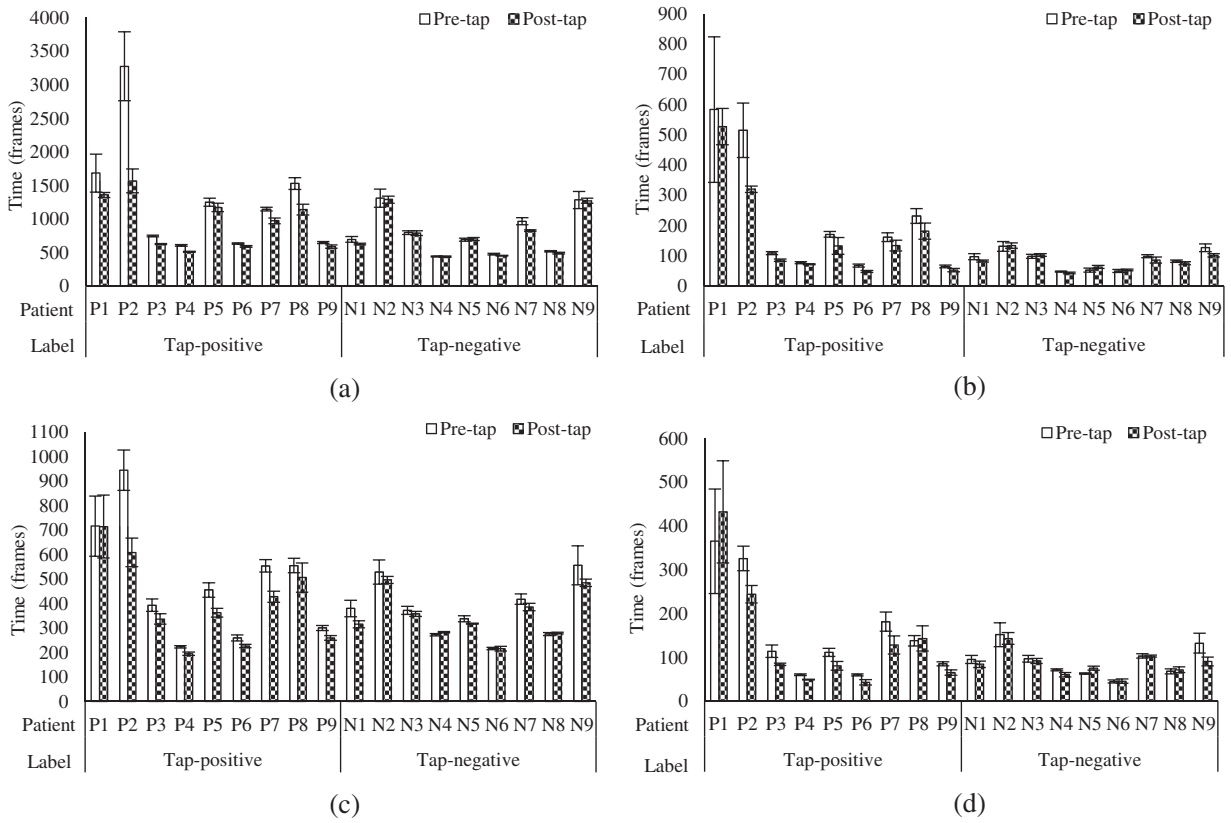

Fig. 3. Time measurements, as shown by the average ± standard deviation for the sample mean. The improvement in the total walking time is slightly different from that in Table II, e.g., P1, P3, P8, and P9. This is because the physician uses the best score to judge improvement, while we use the mean and standard deviation for the sample mean. (a) Total time of TWM; (b) turning time in TMW; (c) total time of TUG; (d) turning time in TUG

Table II. The P-values of all gait features and walking time measurements

	The P-value of							
Patient no.	Lateral sway	Petit-pas gait	wide-base gait	Duck-footed walking	Total time of TMW	Turning time in TMW	Total time of TUG	Turning time in TUG
P1	**0.006**	0.059	0.824	0.990	0.144	0.412	0.496	0.649
P2	0.244	0.032	0.044	0.038	0.006	0.034	**0.004**	0.020
P3	0.061	0.001	0.999	0.825	**7.E-06**	0.002	0.060	0.040
P4	0.485	0.021	0.809	0.519	**2.E-05**	0.101	0.013	4.E-04
P5	0.105	0.198	0.988	**0.003**	0.213	0.190	0.016	0.054
P6	0.036	0.174	0.381	0.912	0.016	**0.004**	0.017	0.034
P7	0.105	0.006	0.120	0.052	0.009	0.137	**0.002**	0.054
P8	0.576	0.005	0.158	0.184	**0.003**	0.102	0.251	0.562
P9	**3.E-05**	0.010	0.362	0.407	0.043	0.072	0.008	0.021
N1	0.697	0.278	0.426	0.657	0.078	0.100	**0.053**	0.194
N2	**0.090**	0.724	0.414	0.513	0.451	0.564	0.274	0.388
N3	0.283	0.957	**0.122**	0.768	0.420	0.731	0.241	0.308
N4	0.145	0.291	0.872	0.153	0.429	0.116	0.956	**0.114**
N5	**0.059**	0.503	0.158	0.730	0.610	0.874	0.076	0.968
N6	0.951	0.865	0.455	0.304	**0.088**	0.691	0.462	0.536
N7	0.230	0.389	0.402	0.130	**0.018**	0.195	0.131	0.500
N8	0.185	**0.020**	0.408	0.827	0.075	0.139	0.704	0.666
N9	0.109	0.555	0.848	0.427	0.467	**0.062**	0.211	0.072

The minimum P-value of each patient is marked in bold.

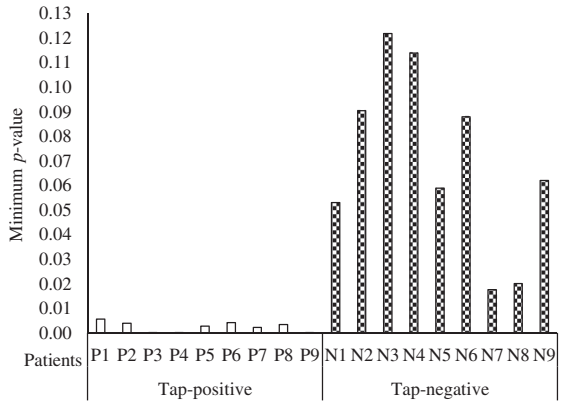

Fig. 4. The minimum P-values calculated for each patient. Although the minimum P-value for two tap-negative patients were <0.05, the minimum P-value for tap-positive patients were generally smaller than for tap-negative patients

Next, we will further discuss the challenges encountered in the development of our methodology, including some inconsistencies in lateral sway, and compare our method to that used by the physicians.

4.1. Lateral sway According to the definition of lateral sway in the GSSR, a score of 2 indicates a fluctuation in the patient's heel strike position, a score of 1 indicates trunk sway, and a score of 0 indicates no sway or heel strike abnormality. Because our proposed method assesses trunk sway, it was expected to appropriately reflect the 0 and 1 scores. However, during our interviews with the physicians, the physicians stated that they assigned a score of 1 to patients who exhibited a trunk sway or those with a small degree of heel strike fluctuation, while they only assigned a score of 2 when frequent fluctuations in heel strike position were observed. Thus, we asked the physicians to reassess lateral sway using the strict definition of GSSR, which provided more consistency in the assessed values between our video-based analysis and the physicians' judgment. This is because physicians often associated lateral sway with a sense of balance during walking, and therefore, associated the frequency of fluctuations in heel strike with lateral sway scores. Thus, we suggest that the inconsistency of findings using our method compared with physicians' judgment is derived, at least in part, from differences in understanding of the definitions.

The ambiguity of the subjective judgment also influences the judgment of the physicians. From the interviews, we found that physicians often assign a better lateral sway score to patients exhibiting a lateral sway than that derived from iNPH. For example, physicians assigned a score of 0 to a patient walking fast during the test despite the presence of lateral sway because typical iNPH patients walk slowly. A lateral sway derived from fast walking was considered unimportant when rating the lateral sway for iNPH. Another patient was assigned a score of 0 despite the presence of a body sway because she had no petit-pas gait, wide-base gait, duck-footed walking, or other typical features of iNPH gait disturbance. Thus, the physicians felt that the sway was from another cause. As such, the judgment of the physicians often deviated from the definition of lateral sway.

4.2. Wide-base gait and duck-footed walking As previously described, we assessed the wide-base gait and duck-footed walking features of all patients using a selected subsequence of two gait cycles in which the patients walked stably. We asked the physicians to review the selected gait segment, and they confirmed that the assigned values for these sequences were reasonable. Thus, we concluded that the proposed silhouette analysis-based method for wide-base gait and duck-footed walking was appropriate.

However, physicians assessed the entire gait sequence, which includes the stable gait sequence as well as the unstable gait sequence that often occurs when the patient turns or begins to walk. As such, our proposed method may miss gait disturbances if they are observed outside of our selected sequence. The assessed values of several patients with walking labels that were inconsistent with physician observations may relate to this subsequence selection problem. In future studies, we will extend our analysis to the entire gait sequence.

5. Conclusion

We propose a video-based method to improve gait disturbance assessment for iNPH. The proposed method can assess gait features independently of a physician's experience, and we validated that the method using the assessed value is more accurate than current qualitative methods for judging the CSF tap test. We assessed lateral sway, petit-pas gait, wide-base gait, and duck-footed walking, as well as the walking times, of the tests using gait silhouette analysis. We confirmed the effectiveness of our proposed method with experiments on the CSF tap test judgment with nine tap-positive and nine tap-negative patients.

Some of the assessed values, however, remained partially inconsistent with the GSSR scores assigned by the physicians. One reason for this failure is that the proposed gait feature

Table III. The corresponding features of each patient's minimum P-value and the assessment values

Patient		P1	P2	P3	P4	P5	P6	P7	P8	P9
Feature		Lateral sway	Total time of TUG (s)	Total time of TMW (s)	Total time of TMW (s)	Duck-footed walking (ratio)	Turning time in TMW (s)	Total time of TUG (s)	Total time of TMW (s)	Lateral sway (%)
Pre-tap	Mean	1.20	944.8	745.6	607.5	2.56	67.5	533.5	1528.6	1.60
	SD	0.06	82.3	12.8	11.6	0.03	5.2	25.3	86.0	0.03
Post-tap	Mean	1.01	608.5	627.5	511.7	2.44	47.5	427.5	1138.8	1.41
	SD	0.04	58.3	7.8	6.0	0.02	3.2	23.1	80.7	0.03

Patient		N1	N2	N3	N4	N5	N6	N7	N8	N9
Feature		Total time of TUG (s)	Lateral sway (%)	Wide-base gait (%)	Turning time in TUG (s)	Lateral sway (%)	Total time of TMW (s)	Total time of TMW (s)	Petit-pas gait (m)	Turning time in TMW (s)
Pre-tap	Mean	379.4	1.93	1.56	71	1.23	474.4	965.6	0.66	126.5
	SD	33.4	0.06	0.52	2.3	0.04	12	52.6	0.01	12.9
Post-tap	Mean	315	1.83	0.73	60	1.16	455	827.5	0.71	101.5
	SD	14.3	0.03	0.3	5	0.02	5	12.5	0.02	5.5

extraction and assessment method is different from the physicians' own customized criteria for GSSR. Future studies are required to improve our proposed method by considering the frequency of fluctuations in each patient's heel strike position and the multifactorial dependency of the GSSR.

Another potential issue for clinical application of our method is that the manual work (e.g., silhouette modification, bounding box assigning, and step counting) is time consuming. To improve this, we are currently examining automatic extraction of the silhouette using a deep learning-based method (e.g., the RefineNet [36]). In future studies, we will also capture kinematic information of patients using depth sensors for more intuitive and accurate assessment of the features.

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References

(1) Hakim S, Adams RD. The special clinical problem of symptomatic hydrocephalus with normal cerebrospinal fluid pressure: Observations on cerebrospinal fluid hydrodynamics. *Journal of the Neurological Sciences* 1965; **2**(4):307–327.

(2) Iseki C, Kawanami T, Nagasawa H, Wada M, Koyama S, Kikuchi K, Arawaka S, Kurita K, Daimon M, Mori E, Kato T. Asymptomatic ventriculomegaly with features of idiopathic normal pressure hydrocephalus on MRI (AVIM) in the elderly: A prospective study in a Japanese population. *Journal of the Neurological Sciences* 2009; **277**(1):54–57.

(3) Tanaka N, Yamaguchi S, Ishikawa H, Ishii H, Meguro K. Prevalence of possible idiopathic normal-pressure hydrocephalus in Japan: The Osaki-Tajiri project. *Neuroepidemiology* 2009; **32**(3):171–175.

(4) Mori E, Ishikawa M, Kato T, Kazui H, Miyake H, Miyajima M, Nakajima M, Hashimoto M, Kuriyama N, Tokuda T, Ishii K, Kaijima M, Hirata Y, Saito M, Arai H; Japanese Society of Normal Pressure Hydrocephalus. Guidelines for management of idiopathic normal pressure hydrocephalus. *Neurologia Medico-Chirurgica* 2012; **52**(11):775–809.

(5) Krauss JK, Regel JP, Vach W, Droste DW, Borremans JJ, Mergner T. Vascular risk factors and arteriosclerotic disease in idiopathic normal-pressure hydrocephalus of the elderly. *Stroke* 1996; **27**(1):24–29.

(6) Mori K. Management of idiopathic normal-pressure hydrocephalus: A multi-institutional study conducted in Japan. *Journal of Neurosurgery* 2001; **95**(6):970–973.

(7) Vassilouthis J. The syndrome of normal-pressure hydrocephalus. *Journal of Neurosurgery* 1984; **61**(3):501–509.

(8) Kitagaki H, Mori E, Ishii K, Yamaji S, Hirono N, Imamura T. CSF spaces in idiopathic normal pressure hydrocephalus: Morphology and volumetry. *American Journal of Neuroradiology* 1998; **19**(7):1277–1284.

(9) Wikkelsø C, Andersson H, Blomstrand C, Lindqvist G. The clinical effect of lumbar puncture in normal pressure hydrocephalus. *Journal of Neurology, Neurosurgery, and Psychiatry* 1982; **45**(1):64–69.

(10) Stolze H, Kuhtz-Buschbeck JP, Drücke H, Jöhnk K, Diercks C, Palmie S, Mehdorn HM, Illert M, Deuschl G. Gait analysis in idiopathic normal pressure hydrocephalus-which parameters respond to the CSF tap test? *Clinical Neurophysiology* 2000; **111**(9):1678–1686.

(11) Graff-Radford NR, Godersky JC. Normal-pressure hydrocephalus: Onset of gait abnormality before dementia predicts good surgical outcome. *Archives of Neurology* 1986; **43**(9):940–942.

(12) Fisher CM. Hydrocephalus as a cause of disturbances of gait in the elderly. *Neurology* 1982; **32**(12):1358–1358, 1363.

(13) Podsiadlo D, Richardson S. The timed "up & go": A test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society* 1991; **39**(2):142–148.

(14) Chivukula S, Tempel ZJ, Zwagerman NT, Newman WC, Shin SS, Chen C, Gardner PA, McDade EM, Ducruet AF. The dynamic gait index in evaluating patients with Normal pressure hydrocephalus for cerebrospinal fluid diversion. *World Neurosurgery* 2015; **84**(6):1871–1876.

(15) Sankey EW, Jusue-Torres I, Elder BD, Goodwin CR, Batra S, Hoffberger J, Lu J, Blitz AM, Rigamonti D. Functional gait outcomes for idiopathic normal pressure hydrocephalus after primary endoscopic third ventriculostomy. *Journal of Clinical Neuroscience* 2015; **22**(8):1303–1308.

(16) Agerskov S, Wallin M, Hellström P, Wikkelsö C, Tullberg M. The role of hypertension and diabetes mellitus in the severity of gait and balance disturbances in iNPH. *Fluids and Barriers of the CNS* 2015; **12**(Suppl. 1):O11.

(17) Hellström P, Klinge P, Tans J, Wikkelsø C. A new scale for assessment of severity and outcome in iNPH. *Acta Neurologica Scandinavica* 2012; **126**(4):229–237.

(18) Yogo M, Omoto S, Morita M, Suzuki M. The quantitative motion analysis using portable gait rhythmogram after CSF drainage in the patients with idiopathic normal pressure hydrocephalus. *Fluids and Barriers of the CNS* 2015; **12**(Suppl. 1):P57.

(19) Agostini V, Lanotte M, Carlone M, Campagnoli M, Azzolin I, Scarafia R, Massazza G, Knaflitz M. Instrumented gait analysis for an objective pre-/postassessment of tap test in normal pressure hydrocephalus. *Archives of Physical Medicine and Rehabilitation* 2015; **96**(7):1235–1241.

(20) Armand S, Allet L, Landis T, Beauchet O, Assal F, Allali G. Interest of dual-task-related gait changes in idiopathic normal pressure hydrocephalus. *European Journal of Neurology* 2011; **18**(8):1081–1084.

(21) Man J, Bhanu B. Individual recognition using gait energy image. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 2006; **28**(2):316–322.

(22) Makihara Y, Sagawa R, Mukaigawa Y, Echigo T, Yagi Y. Gait recognition using a view transformation model in the frequency domain. In *Computer Vision - ECCV 2006*. Springer: Berlin, Heidelberg; 2006; 151–163.

(23) Collins RT, Gross R, Shi J. Silhouette-based human identification from body shape and gait. *Proceedings of Fifth IEEE International Conference on Automatic Face Gesture Recognition*, 2002; 366–371.

(24) Wang L, Tan T, Ning H, Hu W. Silhouette analysis-based gait recognition for human identification. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 2003; **25**(12):1505–1518.

(25) Iwama H, Muramatsu D, Makihara Y, Yagi Y. Gait verification system for criminal investigation. *Information and Media Technologies* 2013; **8**(4):1187–1199.

(26) Okumura M, Makihara Y, Nakamura S, Morishima S, Yagi Y. The online gait measurement for the audience-participant digital entertainment. *Invited Workshop on Vision Based Human Modeling and Synthesis in Motion and Expression*, 2009.

(27) Yu S, Tan T, Huang K, Jia K, Wu X. A study on gait-based gender classification. *IEEE Transactions on Image Processing* 2009; **18**(8):1905–1910.

(28) Makihara Y, Okumura M, Iwama H, Yagi Y. Gait-based age estimation using a whole-generation gait database. *2011 International Joint Conference on Biometrics (IJCB)*, 2011; 1–6.

(29) Stone EE, Skubic M. Passive in-home measurement of stride-to-stride gait variability comparing vision and Kinect sensing. *2011 Annual international conference of the IEEE engineering in medicine and biology society*, IEEE, 2011; 6491–6494.

(30) Nguyen TN, Huynh HH, Meunier J. Extracting silhouette-based characteristics for human gait analysis using one camera. *Proceedings of the Fifth Symposium on Information and Communication Technology*. ACM, 2014;171–177.

(31) Liao TY, Miaou SG, Li YR. A vision-based walking posture analysis system without markers. *2010 2nd International Conference on Signal Processing Systems*, IEEE, 2010; 254.

(32) Kubo Y, Kazui H, Yoshida T, Kito Y, Kimura N, Tokunaga H, Ogino A, Miyake H, Ishikawa M, Takeda M. Validation of grading scale for evaluating symptoms of idiopathic normal-pressure hydrocephalus. *Dementia and Geriatric Cognitive Disorders* 2007; **25**(1):37–45.

(33) Rother C, Kolmogorov V, Blake A. Grabcut: Interactive foreground extraction using iterated graph cuts. *ACM transactions on graphics (TOG)*, ACM, 2004; 309–314.

(34) Wikkelsø C, Andersson H, Blomstrand C, Lindqvist G, Svendsen P. Predictive value of the cerebrospinal fluid tap-test. *Acta Neurologica Scandinavica* 1986; **73**(6):566–573.
(35) Ravdin LD, Katzen HL, Jackson AE, Tsakanikas D, Assuras S, Relkin NR. Features of gait most responsive to tap test in normal pressure hydrocephalus. *Clinical Neurology and Neurosurgery* 2008; **110**(5):455–461.
(36) Lin G, Milan A, Shen C, Reid I. Refinenet: Multi-path refinement networks for high-resolution semantic segmentation. *IEEE conference on computer vision and pattern recognition (CVPR)*, 2017; 3.

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