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Estimation of Forward Tilt Angle during Wheelchair Use Considering Back Curvature

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Abstract— **This study proposes a method of estimating the forward tilt angle using an illuminance sensor, focusing on changes in the illuminance value of the seat surface due to changes in the posture during wheelchair use, for the purpose of preventing wheelchair accidents. The effectiveness of the proposed method was tested by fixing the position of the wheelchair and installing an illuminance sensor at the center of the rearmost part of the seat surface. The proposed equation was proposed by measuring illuminance values using a board as a preliminary experiment, and then three healthy subjects measured illuminance values five times per person as in the preliminary experiment and compared them with the proposed equation. The comparison showed that the proposed equation and the measured values had errors due to the curvature of the back, so a correction method that takes into account the curvature of the back during forward tilt was studied and the results were discussed. The results showed that the proposed correction method reduced the error of the forward tilt angle on average, and the error accuracy of the forward tilt angle estimation was within 3 °, with an average error reduction rate of approximately 23.5%.**

I. INTRODUCTION

According to a survey by the Ministry of Health, Labour and Welfare (MHLW), approximately 45% of the disabled people in Japan in 2016 were physically disabled people suffering from spinal cord injury or cerebral palsy [1]. The number of such persons was about 1.93 million as of 2016, and the number has been increasing since 1987 [1]. Because people with physical disabilities have difficulty walking on their own, wheelchairs are used as a mobility aid [2]. There are different types of wheelchairs, such as manual and electric, and their use depends on the degree of the user's disability. Approximately 65% of wheelchair users have experienced falls or tumbles from their wheelchairs [3], making it difficult for them to return to a stable position on their own when they are in an unexpected posture. Therefore, it is important to estimate the posture of a user during wheelchair operation in order to prevent accidents from occurring. In addition, it is expected that quantitative understanding of changes in the forward tilt angle will contribute to maintaining the health and improving the safety of wheelchair users.

Conventional studies on the posture of wheelchair users have mainly used pressure sensors. In a study by Vermander et al [4], a total of 16 pressure sensors, eight on the seat and eight on the back of a wheelchair, were installed to estimate forward tilt and left/right body tilt based on the ratio of pressure values on the seat and back. Forward tilt is defined as a state in which the back is tilted forward about 40 °, and left-right body tilt is defined as the back contacting the backrest while the trunk shifted laterally by 15 to 20 °. This database and pressure values are used to classify postures. This study was able to classify postures with an accuracy of approximately 95%, but it was not able to determine the degree of tilting when tilting forward or to the left or right. In a study by Kini et al [5], three pressure sensors were installed on the seat and an ultrasonic sensor on the back to determine postural stability. The ultrasonic sensor measures the distance between the back of the wheelchair and the back, and in combination with the values from the pressure sensors, classifies the user into one of three types of unstable sitting postures: forward, right or left tilt. This study is able to identify inappropriate sitting posture in over 99% of cases, but it is difficult to estimate the degree to which the body is tilted. In the study by Perez et al [6], eight pressure sensors were installed on the seat and back of the wheelchair as in the study by Vermander et al. In addition, the wheelchair is equipped with an IMU that integrates a 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetic sensor, enabling accurate measurement of rotational and linear motion in three dimensions. It also features a posture monitoring system that incorporates proximity sensors to record tire mileage, temperature and humidity sensors mounted on the rear, and FSR sensors, which are pressure sensors, in the body, seat, armrests, and backrest. A posture monitoring system designed with FSR sensors was installed on the body, seat, armrests, and backrest to evaluate posture stability based on the correlation between the angle and speed of the wheelchair and pressure values. Although the system can make real-time measurements, it uses a large number of sensors, which increases the amount of data and increases the cost. In a study by Chénier et al [7], motion capture was installed on the upper arms, forearms, chest, and head to measure the position of the center of gravity of the whole body. In this study, the subjects had different trunk functions, which resulted in measurement errors. In addition, the method of attaching multiple sensors to the body has issues in terms of user comfort and practicality of implementation. In these studies, it is possible to evaluate the stability of the sitting posture, but it is not possible to directly and quantitatively estimate continuous physical changes such as the forward tilt angle. Pressure distribution, which is an indicator of posture stability, may indirectly suggest subtle changes in posture, but it often requires complex sensor configurations.

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On the other hand, directly estimating continuous physical parameters such as forward tilt angle enables a simpler and more quantitative understanding of dynamic posture changes. This approach is considered to be useful not only for early detection of posture deterioration but also for effective safety management.

When operating a manual wheelchair, some users move their own body away from the backrest and tilt forward to operate the wheelchair wheels to move forward [8]. The operation also causes the body to tilt forward. However, if the wheelchair comes into contact with an unintended obstacle or an unpredictable situation occurs during wheelchair operation, the user is at risk of falling forward. This safety issue may affect the user's safety and convenience. Therefore, to ensure safety, it is necessary to make a decision immediately when an unintended posture occurs. In conventional studies, many sensors are often used to estimate the posture of wheelchair users, which increases the amount of data collected. This not only increases the complexity of data processing but also may affect user comfort due to the physical burden of attaching multiple sensors to the body or wheelchair and the limited space in the seating area. The objective of this study is to propose a method that not only improves the safety of manual wheelchair users during movement but also enables posture estimation during forward tilt using minimal data and a minimal sensor configuration.

II. PROPOSED METHOD

A. Posture Estimation When Tilting Forward

When operating a wheelchair, a forward tilt is performed [8]. When tilting forward, the back and the backrest are separated, so light shines into the last part of the seat surface, and the amount of light changes as the user tilts forward, resulting in a change in the illuminance value of the seat surface. Based on the above, the equation relating the angle of forward tilt and illuminance is assumed to be as shown in Equation (1). θ [°] is the angle of forward tilt, l_θ [lx] is the illuminance value at a certain angle , and l_0 [lx] is the illuminance value when no one is sitting in the wheelchair. The maximum forward tilt angle was set to 40 °because the forward tilt of a wheelchair user is defined as 40 °based on the study by Jaffery et al [9].

$$l_\theta = l_0 \times \frac{\theta}{40} \tag{1}$$

B. Posture Estimation Considering Back Curvature

Equation (1) implies that the illuminance value increases linearly with the angle of forward tilt, but when humans tilt forward, their backs do not form a straight line, and they tilt forward while curving [10]. Therefore, it is necessary to introduce a correction method that takes into account the measurement error caused by the curvature of the back. The spine is deeply involved in the curvature of the back, which consists of five regions: the cervical spine, thoracic spine, lumbar spine, sacrum, and coccyx [11]. Ratios were calculated as in equation (2) to determine the sitting height S [m] from the wheelchair user's height H [m], and the heights of the iliac crest P_1 [m], the inferior angle of the scapula P_2 [m], and the cervical vertebra P_3 [m] in a seated posture were calculated from the ratio of the sitting height S [12].

$$S = 0.540H,\ P_1 = 0.248S,\ P_2 = 0.493S,\ P_3 = 0.720S \tag{2}$$

P_1 to P_3 are the heights from the seat surface. Bezier curves are created using these control points P_1 to P_3 and the seat surface point P_0 to correct the illuminance value.

C. Correction Method

As shown on the left side of Fig. 1, control points P_0 to P_3 were determined. P_0 is the buttocks, P_1 is the iliac crest, P_2 is below the scapula, and P_3 is the lowest cervical vertebra. As shown on the right side of Fig. 1, the curvature of the back was created using a third-order Bezier curves from those control points, as shown in equation (3). dx and dy are values obtained from the seat height S as in equation (4). The Bezier curves were discretized into 1,000 points for each forward tilt angle, and the curves were drawn as solid lines. The dashed lines are the theoretical straight lines, obtained from equation (1). The coordinates at each angle of controllable points P_0 to P_3 were determined by the parameters shown in equation (5). P_0 is the point closest to the backrest where the user's body and the seat of the wheelchair come into contact, and this point is the origin of the Bezier curve.

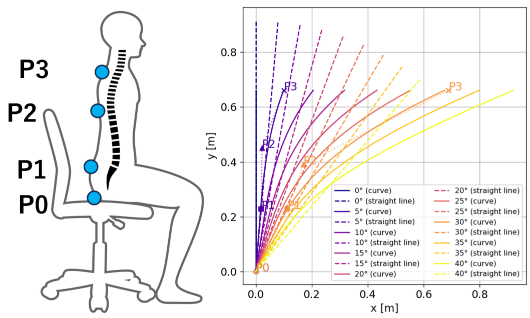

Fig. 1. Bezier curves at each angle obtained from control points P_0 to P_3 and control points. P_0 is the buttocks, P_1 is the iliac crest, P_2 is below the scapula, and P_3 is the lowest cervical vertebra. The Bezier curves are calculated from equation (3) and drawn by discretizing them into 1,000 points for each forward tilt angle. The solid lines are the Bezier curves, and the dashed lines are the theoretical straight lines obtained from (1).

P_1 to P_3 are points that change depending on the forward tilt angle, with $\alpha_1 = 0.3$, $\alpha_2 = 0.32 + 0.0035 \cdot \theta$, $\alpha_3 = 1.2 + 0.01 \cdot \theta$, $r_1 = 0.248$, $r_2 = 0.493$, and $r_3 = 0.720$. The rate of change of the control points of the Bezier curve for each forward tilt angle used in this study was not based on biological structures or musculoskeletal models, but was arbitrarily set according to the behavior of the illuminance distribution. Specifically, as the forward tilt angle increased, the X and Y positions of control points P1 to P3, and the curvature amount R of the back corresponding to the forward tilt angle, were changed in stages to reproduce the nonlinear curvature associated with forward tilt of the back. Such arbitrary settings offer the advantage of flexible adjustments that reflect individual differences in the rate of change of control points. Subsequently, the maximum volume $V_{\max}$ obtained from the straight line in equation (1) was calculated using the area of the triangle formed by dx and dy and the sensor width w, as shown in equation (6), and the shaded volume V_{shade} of the region where the Bezier curve is to the left of the straight line in equation (1) was calculated as shown in equation (7). x_{diff} is the sum of the x-direction differences between the straight line and the Bezier curve in the region where the Bezier curve is to the left of the straight line in equation (1). Δy was defined as the difference between the lower 5th percentile value $y_{5\%}$ and the upper 95th percentile value $y_{95\%}$ of the y coordinates on the Bezier curve in the area considered to be shaded, and this difference $\Delta y = y_{95\%} - y_{5\%}$ was defined as the " effective height " of the shaded area. The sensor width w is 0.05 [m]. Then, the shielding rate ρ is calculated as in equation (8), and the shielding illuminance value $\hat{l}_\theta$ at a certain angle is calculated as in equation (9).

$$B(t) = (1-t)^3 P_0 + 3(1-t)^2 t P_1 + 3(1-t)t^2 P_2 + t^3 P_3, \quad t \in [0,1] \tag{3}$$

$$dx = S \cdot \sin(\theta), \quad dy = S \cdot \cos(\theta) \tag{4}$$

$$\begin{aligned} P_0 &= (0,\ 0) \\ P_1 &= (\alpha_1 \cdot dx + R,\ S \cdot r_1) \\ P_2 &= (\alpha_2 \cdot dx + R,\ S \cdot r_2 + \beta \cdot (dy - L)) \\ P_3 &= (\alpha_3 \cdot dx,\ S \cdot r_3) \end{aligned} \tag{5}$$

$$V_{\max} = \frac{1}{2} \cdot dx \cdot dy \cdot w \tag{6}$$

$$V_{\text{shade}} = \sum x_{\text{diff}} \cdot \Delta y \cdot w \tag{7}$$

$$\rho = \frac{V_{\text{shade}}}{V_{\max}} \tag{8}$$

$$\hat{l}_\theta = l_\theta \cdot (1 - \rho) \tag{9}$$

III. PRELIMINARY EXPERIMENT

A. Measurement Method

In this experiment, a manual wheelchair (CAH-50SU, Care-Tec Japan, Japan), an illuminance sensor (IWS660-CS, Tokyo Devices, Japan), and a Black board 0.500 [m] long, 0.395 [m] wide, 0.010 [m] thick were used. This experiment was conducted in a room under standard lighting with uniform illumination to eliminate the influence of the lighting environment. The position of the wheelchair was fixed, and an illuminance sensor was placed at the center of the rearmost part of the seat, as shown in Fig. 2. The blackboard represented the human back, with the contact point between the backrest and the wheelchair defined as 0 °. Illuminance was measured while tilting the board in 5 °increments from 0 °to 40 °. These measurements were made five times in total, and each measurement was plotted on a graph with the angle on the horizontal axis and the illuminance value on the vertical axis. The illuminance values were obtained by connecting the illuminance sensor to a PC with a USB cable. Angles were measured by attaching a protractor to the wheelchair.

Fig. 2. Measurement method using illuminance sensor, one illuminance sensor in the center of the rearmost part of the seat of the wheelchair.

B. Measurement Result

Fig. 3 shows the results of one of the five measurements of illuminance values. The horizontal axis is the angle of forward tilt [°] and the vertical axis is the illuminance value [lx]. The orange line is the theoretical value obtained from the initial illuminance value $l_o = 479.5$ lx and equation (1), and the blue line is the measured value. The experimental results in Fig. 3 show that the average error of the illuminance value between the proposed equation and the measured value is 12.8 lx, which is 1.20 °in the forward tilt angle. The average error of the illuminance values for the entire five measurements was 21.8 lx which is 2.06 °in the forward tilt angle. Fig. 3 shows that the illuminance value increases approximately linearly with the angle of forward tilt. Therefore, the proposed equation is valid.

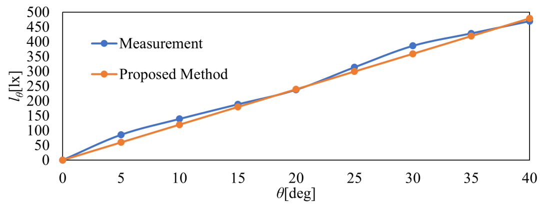

Fig. 3. Relationship between forward tilt angle and illuminance value and comparison with proposed method. The horizontal axis is the angle of forward tilt angle θ [°] and the vertical axis is the illuminance value $l(\theta)$ [lx]. The orange line is the theoretical value obtained from the initial illuminance value $l_o = 479.5$ lx and equation (1), and the blue line is the measured value.

IV. VALIDATION OF EFFECTIVENESS

This section shows the experimental procedures conducted by the subjects and the results without correction in IV-A, and the results after correction using the proposed correction method in IV-B.

A. Experiment Without Correction

Preliminary experiments have confirmed that the illuminance value increases approximately linearly with the angle of forward tilt in the case of a board. However, since the purpose of this experiment is to estimate the forward tilt angle of wheelchair users, the validity of the proposed equation was confirmed by experiments with human subjects.

1) Measurement Method: Preliminary experiments showed that the maximum illumination was obtained when the forward tilt angle was 40 °. The landmark was placed on the seventh cervical vertebra (C7), which is responsible for the balance of the back curve and is easily palpable [10]. The illuminance values were then measured at 5 °intervals from 0 to 40 °using the landmark, as shown in Fig. 4. A total of three subjects performed the measurements, with each subject taking five measurements. The experimental environment was the same as in the preliminary experiment. In each measurement, the illuminance value was first measured when no one was seated, and this time was used as the initial illuminance value. Three healthy male subjects in their 20s were used in this experiment. The clothing worn by the subject of the study was of a standard design, without any protrusions such as hoods or large collars. The subjects were 1.65 m, 1.72 m, and 1.70 m in height, starting from the first subject. All subjects signed an informed consent statement prior to participation in the study.

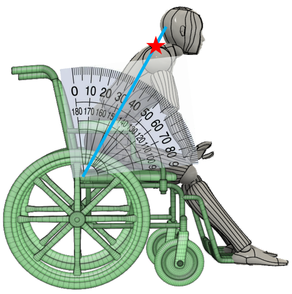

Fig. 4. Schematic Diagram of the Experiment. The illuminance values were then measured at 5 °intervals from 0 to 40 °using the landmark. The red star shows the landmark position set for this experiment, which is the seventh cervical vertebra (C7).

2) Measurement Result: Fig. 5 shows the results of one of the five experiments with three subjects, with the horizontal axis representing the angle of forward tilt and the vertical axis representing the illuminance value. From the top of Fig. 5, these are the results for the first, second, and third subjects. The orange line is the theoretical value obtained from the initial illuminance value of the first person to l_0=452.9 lx, 447.8 lx, 399.6 lx and equation (1), and the blue line is the measured value, and the gray dots are the average value and standard deviation of five times. Fig. 5 shows that the illuminance values of all three subjects increased approximately linearly with the angle of forward tilt, but after 25 °, the difference between the measured illuminance values and the proposed equation tended to increase and the deviation also increased. Overall, the measured illuminance values are smaller than those of the proposed equation. Table 1 shows the results of calculating the average error illuminance values l_e for each measurement after correcting the results obtained in this experiment. The rows show the average error illuminance values for each measurement and the error illuminance values for all five measurements, while the columns show the illuminance value errors l_e for each of the three subjects. Table 2 shows the conversion of the illuminance value errors l_e in Table 1 into the error angles x_e. The error angle x_e was calculated from the ratio of the initial illuminance value l_0 and the error illuminance value l_e, as shown in Equation (10).

$$l_0 : 40 = l_e : x_e \tag{10}$$

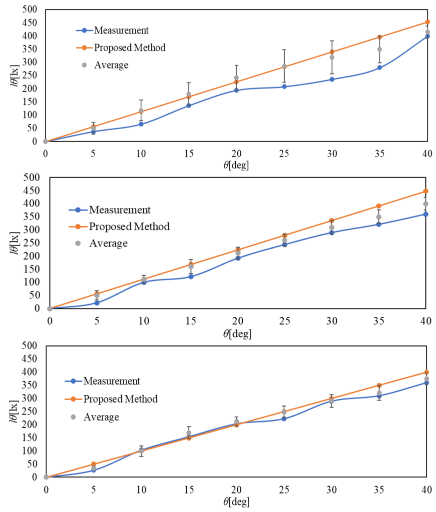

Fig. 5. Relationship between forward tilt angle and illuminance value and comparison with proposed method. The horizontal axis is the angle of forward tilt θ [°] and the vertical axis is the illuminance value $l(\theta)$ [lx]. Results of one of the five measurements for the first, second, and third subjects from the top. The orange line is the theoretical value obtained from the initial illuminance value of the first person to lo=452.9 lx, 447.8 lx, 399.6 lx and equation (1), and the blue line is the measured value, and the gray dots are the average value and standard deviation of five times.

TABLE I
ILLUMINANCE VALUE ERROR BETWEEN MEASUREMENTS AND PROPOSED METHOD.

Time	Illuminance Value Error l_e [lx]		
	Subject 1	Subject 2	Subject 3
1st	19.0	40.7	21.6
2nd	39.9	19.5	24.6
3rd	53.6	19.3	21.0
4th	33.1	24.2	16.8
5th	42.8	24.1	11.1
Average	37.7	25.6	19.0

TABLE II
FORWARD TILT ANGLE ERROR BETWEEN MEASUREMENTS AND PROPOSED METHOD.

Time	Forward Tilt Angle Error x_e [°]		
	Subject 1	Subject 2	Subject 3
1st	1.6	3.6	2.0
2nd	3.4	1.7	2.4
3rd	4.7	1.7	2.2
4th	2.9	2.2	1.7
5th	3.8	2.2	1.1
Average	3.3	2.3	1.9

B. Experiment With Correction

The measurement results of the main experiment showed that the illuminance value tended to be smaller than that of the proposed equation due to an error in the illuminance value compared to the proposed equation. This is due to the fact that when people tilt forward, their backs are not in a straight line but are curved as they tilt forward, and the curvature becomes larger as the angle of forward tilt becomes larger. Therefore, as the angle increases, the illuminance error is expected to increase. Corrections were considered to reduce these errors.

1) Measurement Method: The experiment was conducted based on the measurement values obtained in the main experiment. The corrected illuminance values were calculated using equations (3) to (9). When the illuminance value at 10 °was lower than the illuminance value obtained from equation (1), it was determined that the illuminance sensor was blocked by the curvature of the back, and the measurement value was corrected by adding the corrected illuminance value. In other cases, no correction was applied as the measurement did not meet the proposed criteria. Next, as in the main experiment, a comparison was made with the proposed equation, and the measured values were compared with the corrected results. The value of 10 °was chosen because it was considered to provide relatively stable measurement accuracy and make it easier to observe the overall trend.

2) Measurement Result: Table 3 shows the results of calculating the average error illuminance values l_e for each measurement after correcting the results obtained in this experiment. The rows show the average error illuminance values for each measurement and the error illuminance values for all five measurements, while the columns show the illuminance value errors l_e for each of the three subjects. Table 4 shows the conversion of the illuminance value errors l_e in Table 3 into the error angles x_e using equation (10). Based on the illuminance values at 10 °, measurements that were not corrected occurred twice for all subjects. Fig. 6 compares the measured and corrected illuminance values when the theoretical value is set to 0 lx. The horizontal axis is the forward tilt angle θ [°] and the vertical axis is the error illuminance value $l(\theta)$ [lx]. The results for subjects 1, 2, and 3 are shown from top to bottom. Orange dots are measured values, gray dots are corrected values. The theoretical illuminance value at each angle calculated from the proposed equation is set to 0, and the measured and corrected illuminance values obtained in this experiment and the deviation from the theoretical illuminance value are shown. These values are all calculated from the average of five measurements. Tables 1 to 4 show that although some measurements were uncorrected, the corrected measurements showed a reduction in error for all participants. Among the uncorrected measurements, the percentage of overall illuminance values exceeding the theoretical values was 44% for the fourth measurement of subject 2 and 33% for the fourth measurement of subject 3, but for all other measurements, the percentage was 56% or higher. Overall corrected results showed an average reduction rate of 23.5% compared to the measured values. Regarding the correction results in Fig. 6, it can be seen that the error after correction is greater than the error before correction in subjects 1 and 3 in the range of 10 °to 25 °, and in subject 2 at 10 [°]. However, it can be seen that the error decreases after 30 °in all three subjects.

TABLE III
ILLUMINANCE VALUE ERROR BETWEEN MEASUREMENTS AND PROPOSED METHOD.

Time	Illuminance Value Error l_e [lx]		
	Subject 1	Subject 2	Subject 3
1st	16.4	24.1	15.1
2nd	39.9	4.7	24.6
3rd	36.5	19.3	14.8
4th	33.1	24.2	16.8
5th	25.7	10.7	8.8
Average	30.3	16.6	16.0

TABLE IV
FORWARD TILT ANGLE ERROR BETWEEN MEASUREMENTS AND PROPOSED METHOD.

Time	Forward Tilt Angle Error x_e [°]		
	Subject 1	Subject 2	Subject 3
1st	1.4	2.2	1.4
2nd	3.4	0.42	2.4
3rd	3.2	1.7	1.5
4th	2.9	2.2	1.7
5th	2.3	1.0	0.91
Average	2.6	1.5	1.6

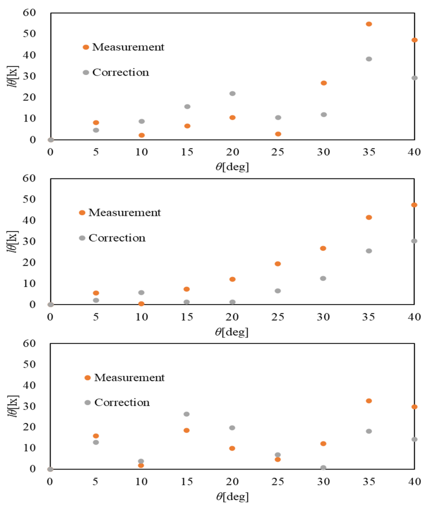

Fig. 6. Comparison of measured and corrected illuminance values when the theoretical value is 0 lx. The horizontal axis is the forward tilt angle θ [°] and the vertical axis is the error illuminance value $l(\theta)$ [lx]. Results for the first, second, and third from the top. The orange dots are the measured values and the gray dots are the corrected values.

V. DISCUSSION

A. Experiment Without Correction

Fig. 5 shows that the measured illuminance values are smaller than the proposed equation. This is thought to be due to the curvature of the back when the subject tilts forward. The reason for the different illuminance values for each subject is thought to be that the degree of curvature of the back differs according to the difference in height, and the reason for the different illuminance values in each measurement case is thought to be that it was difficult for the subjects to assume the same posture completely. Subject 1 showed a particularly large deviation, which may be due to the low reproducibility of the posture during the measurement. It is also possible that the lack of uniformity in clothing types caused errors in the illuminance values. To reduce the error in each measurement, it is thought that attaching landmarks to multiple areas, such as the head as well as the back, is necessary to improve posture reproducibility and to standardize clothing. In 80% of the measurements, the illuminance error increased as the angle of forward tilt increased, which is thought to be due to the fact that the degree of back curvature also increases as the angle of forward tilt increases. In another 20% of the measurements, the measured illuminance values were larger than the proposed equation, but this is thought to be due to errors in the angle of forward tilt or misalignment of the illuminance sensor during forward tilt.

B. Experiment With Correction

As shown in Tables 1 and 3, when illuminance values were compared using the proposed equation, errors decreased in all measurements corrected using the illuminance value at 10 °as a reference, and the overall average error also decreased. In particular, the error decreased by approximately 23.5% compared to before correction, confirming the effectiveness of this correction method quantitatively. When determining the necessity of correction based on illuminance values at a 10 °forward tilt angle, in one-third of the measurements in which correction was not applied showed that the proportion of measured illuminance values exceeding the theoretical values was less than 50% of the total measurement points. In these measurements, the average illuminance error was relatively small at 24.2 lx and 16.8 lx, and the angles were 2.2 °and 1.7 °, respectively, suggesting that the measurement accuracy was high overall. Therefore, although the correction was not applied due to a slight deviation at 10 °, it is considered that no significant error actually occurred. Despite such exceptions, the error decreased in all measurements where the correction was applied, and the average error decreased significantly overall, suggesting that the correction method proposed in this study is effective.

VI. CONCLUSIONS

In this paper, focusing on the change in illuminance between the back and backrest during forward tilt of a wheelchair, a forward tilt estimation method using an illuminance sensor was proposed. This paper described a method for estimating the forward tilt angle using a single illuminance sensor installed at the center of the rearmost part of the seat of a wheelchair, based on changes in illuminance values that occur when a person is tilted forward. The effectiveness of the proposed method was verified by comparing the illuminance values with those of the proposed method, where the position of the wheelchair was fixed and the illuminance was measured at intervals of 5 °from 0 to 40 °. The results of this experiment showed that the illuminance value increased approximately linearly with the angle of forward tilt, but the overall illuminance value tended to be smaller than that of the proposed equation. This is attributed to the curvature of the back during forward tilt, and a corresponding correction method was proposed. Based on the illuminance value at a 10 °tilt, corrections were selectively applied. Effectiveness was verified by comparing deviations between experimental, corrected, and true illuminance values. As a result, the average error of the illuminance value was reduced, and the effectiveness of the correction method was verified. In the future, it is necessary to verify the effectiveness of the proposed equation not only when the wheelchair is stationary, but also when the wheelchair is actually being operated. In addition, since the subjects in this experiment were healthy individuals, it will be necessary to confirm whether the same results can be obtained for wheelchair users in the future.

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