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Development of Gait Analysis System Based on Continuous Plantar Images Obtained Using CaTTaP Device

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Abstract This paper presents a novel gait analysis system that is easy to use by patients and doctors. The system uses a new gait analysis device called "CAterpillar Type trAnsParent treadmill (CaTTaP)" and an image processing method. The CaTTaP has a "caterpillar" type of walking surface made of acrylic resin plates. A camera embedded in the CaTTaP walking surface continuously captures images of the sole during walking. Image processing of the plantar images extracts the plantar regions and determines the position of the subject's sole on the CaTTaP. To evaluate the usefulness of the proposed method, we calculated the step length and width. For this study, we recruited 6 robust elderly persons. We conducted measurements with each subject walking at 3 different velocities. A total of 302 step lengths and widths were calculated from the image data, and the accuracy of the results were estimated by comparing with measurements obtained simultaneously using a motion capture system. Analysis of the absolute values of differences showed that the accuracy of the proposed system varied among subjects. In the higher accuracy group, step length and width were estimated with absolute differences of approximately 16.1 mm and 31.2 mm, respectively, and the entire sole was stably and steadily in ground contact from the heel to the toe. However, in the lower accuracy group, step length and width were estimated with absolute differences of approximately 61.2 mm and 34.4 mm, respectively, and the toes were sometimes off ground. The results suggest that the accuracy of the proposed system varies depending on the type of gait, and that the image processing method requires further improvement. However, the proposed system provides a new approach to gait analysis that requires a short walk and no preparations or special wear. In addition, the CaTTaP has the potential to measure parameters such as the plantar contact area, plantar skin deformation, and shape of the sole with clearer dynamic plantar images that are difficult to obtain continuously by other devices. The novel CaTTaP is one of the best gait analysis systems available for clinical use.

Keywords: plantar image, sole, image processing, gait.

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1. Introduction

Information derived from plantar images serves as a useful, reliable, and objective component in gait analysis. Currana et al. [1] reported the differences between the angle and base of gait from dynamic and static plantar images. Lin et al. [2] constructed a system to investigate the relationship between static balance and foot structure of a child using a footprint image. Hawes et al. [3] measured the foot arch from the ratio of a plantar bearing area and the area of the arch of a foot. Nakajima et al. [4] proposed a method for personal identification based on plantar shape. Shiina et al. [5] suggested a relation between plantar skin deformation and gait stability based on plantar images. Thus, plantar images have been used in various research, but the majority of these studies used static data obtained by walking over paper with the soles covered with powder [1], low resolution data obtained using a pressure mat [4], or data obtained by capturing only one step under a transparent plate [5]. Based on the above findings, although plantar image has great potential, the method to obtain the plantar image is seldom used in clinical applications.

To date, human gait has been analyzed using several methods and various devices and systems such as motion capture systems, accelerometers, pressure distribution measurement systems, electromyography (EMG), and force plates [6]. Motion capture systems can be used to measure physical movements such as the joint angles, and to determine the correlation between a movable range and a part [7]. Moreover, several types of pressure sensors such as the plate type [8], instrumented gait type, and shoe type are used for gait analysis. In addition, a compact accelerometer is often used in various methods because of convenience. Thus, gait analysis comprising joint kinematics, kinetics, and dynamic EMG data is now recognized as a clinically useful tool.

However, despite the apparent value of gait analysis, clinical laboratory testing of locomotor disorders is not widely conducted; this includes conditions related to neuromuscular disorders where gait analysis is most needed. One reason is that the methods require repeat measurements, complicated devices, special wears, or considerable preparation time for measurement and analysis. Thus, conventional devices and systems are difficult to use in the clinical setting. Moreover, use of the gait analysis system depends on subjective judgments such as knowledge, experience, and the visual observation experience of doctors and therapists. Therefore, there is a need for new systems that minimize the time required for gait evaluation, incorporating computer pro-

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gramming techniques that can be used to conduct the evaluation [9].

Recently, instrumented treadmills have been the focus of research because they allow data collection of one or more steps after one trial without special preparations, in a small room equipped with a treadmill. Kram et al. [10] developed a force treadmill to measure the vertical, horizontal, and lateral components of the ground-reaction forces and the ground-reaction force moments. Kalron et al. [11] used the Zebris FDM-T Treadmill fitted with an electronic mat containing force sensors embedded under the belt to examine whether the spatiotemporal parameters were able to distinguish patients with multiple sclerosis from age-, gender-, height- and weight-matched controls. Kale et al. [12] applied videography to record the footprint of mice on a transparent treadmill belt. Gasparini et al. [13] proposed a method of recording the walking tracks for visualization of injured paw. Kale's system allows collection of clear and dynamic footprint data for one or more steps within a short time and immediate gait evaluation. However, it is difficult to use Kale's system for measuring human gait.

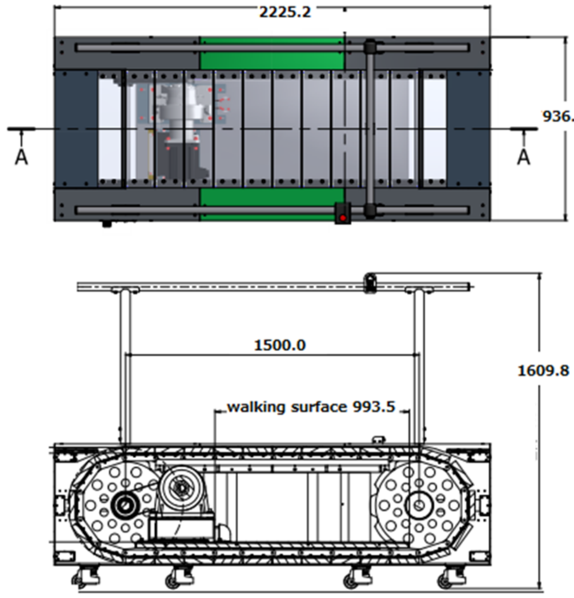
Thus, we are developing a new system to analyze gait using a new treadmill—the Caterpillar type transparent treadmill (CaTTaP)—that continuously captures plantar images during walking. The gait parameters are calculated using the positional information of the sole obtained from plantar image processing. The position of ground contact and contact area of a subject who walks on the CaTTaP are easily calculated. To estimate the usefulness of the proposed method, we calculated the step length and width that cannot be calculated by a normal treadmill, and estimated the accuracy of the results by comparing with measurements obtained using a motion capture system.

2. Proposed system

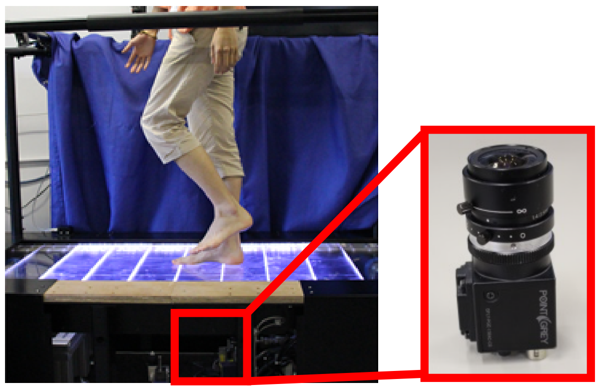
2.1 Caterpillar type transparent treadmill (CaTTaP)

The major feature of our proposed system is a simple device which measures human gait without the need for special preparation or wear. The new device "Caterpillar type transparent treadmill (hereinafter referred to as CaTTaP)" that captures continuous plantar images during walking. **Figure 1a** shows the size of the CaTTaP (dimensions: approximately 940 mm × 2200 mm × 1600 mm; walking surface: approximately 1500 mm × 602 mm). **Figure 1b** shows the appearance of the CaTTaP. The walking surface of the CaTTaP is caterpillar-like and is made of acrylic resin plates as shown in **Figure 1c**. The maximum rolling velocity of the CaTTaP is 6 km/h, and the velocity is controllable at 0.1 km/h. A camera (**Figure 1d**: Point Grey, BFLY-PGE-13E4C-CS, 60 Hz, 1280 × 1024 pixel) is embedded inside the CaTTaP to capture plantar images continuously both when a foot makes ground contact and when the foot is off ground. When a foot makes ground contact, light of LED lamps installed along a walk way reflects diffusely and the part in ground contact appears in the image. When the foot is off ground, only the lines of the plates of the walkway appear in the image. The sole images are processed to obtain positional information of the foot of the person who walks on the CaTTaP.

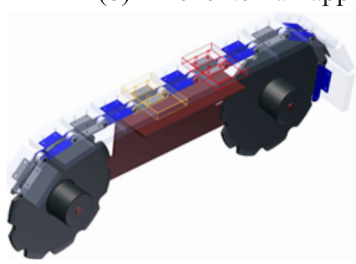
It has been reported that step length varies by 10% at the preferred walking speed [14]. To measure the variation, it is necessary to measure the step length within 5% error. Thus, the resolving power needs to be within 2.5% of the step length. Assuming the step length of human to be 80 cm, 2.5% of step length is 2 cm. The resolution of the camera is 0.5 mm. Thus, the resolution is considered to be sufficient for gait analysis.



(a) Size of the CaTTaP



(b) The external appearance



(c) The walking surface

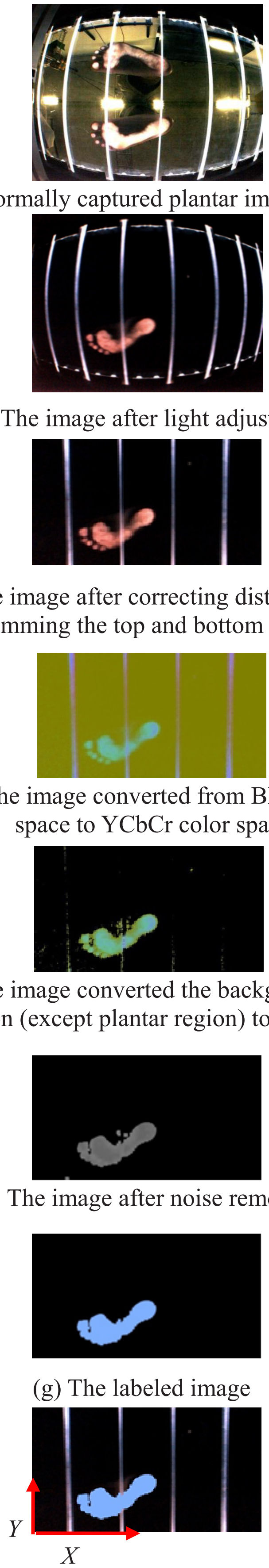
Fig. 1 Caterpillar type transparent treadmill (CaTTaP).

Assuming human walking velocity to be 3 km/h (= 83.3 cm/s) and step length 80 cm, to move 10% of the step length requires approximately 0.096 s. The camera of the CaTTaP captures an image every 0.016 s (60 Hz). Thus, the capturing speed is also adequate for gait analysis.

2.2 Image Processing

2.2.1 Extraction of the plantar region

This section describes image processing. **Figure 2a** shows a plan-



(a) Normally captured plantar image

(b) The image after light adjustment

(c) The image after correcting distortion and trimming the top and bottom space

(d) The image converted from BRG color space to YCbCr color space

(e) The image converted the background region (except plantar region) to black

(f) The image after noise removal

(g) The labeled image

(h) The composed image (**Fig. 2a and 2e**)

Fig. 2 Flow of image processing of the plantar image.

tar image that is captured normally. In the captured plantar image, several vertical lines are visible, which are caused by light reflection. Thus, we extract the plantar region after removing the unnecessary background using the following image processing steps:

i. Capture the plantar image after light adjustment and white balance correction. Light adjustment renders the experiment environment uniform and unnecessary background black. White balance correction distinguishes the plantar region from the background more clearly. This step facilitates image processing (**Figure 2b**).
ii. Correct the distortion that occurs in the case of capturing.
iii. Trim the unnecessary top and bottom space of the images to reduce the amount of calculation (1280 × 1024 pixel to 1280 × 700 pixel per frame) (**Figure 2c**).
iv. Smooth the image to make threshold processing easier by Gaussian filter.
v. Convert the image from RGB color space to YCbCr color space to distinguish the plantar region from the background (**Figure 2d**).
vi. Convert the background region (except plantar region) to black (**Figure 2e**).
vii. Split only Cr channel and remove the noise by opening processing (**Figure 2f**).
viii. Binarize (by Otsu's method) and label (by Imura's method) the image to obtain the coordinates of the plantar region (**Figure 2g**). Areas with different colors in the processed image denote different plantar regions. The mean area of the little toe with the smallest contact area is approximately 370 pixels. Thus, all regions under 350 pixels are removed to reduce the noise. The proposed system decides the size of the region that requires minimum calculation, but does not limit the number of regions. This allows extraction of all types of sole patterns, even special cases such as the divided sole (**Figures 3a and 3b**), the high arch sole (**Figure 3c**) and 2 soles contact the ground at the same time (**Figure 3d**);
ix. Combine the trimmed image (**Figure 2c**) and the labeled image (**Figure 2g**) to facilitate recognition of the position of ground contact (**Figure 2h**).

2.2.2 Extraction accuracy

The accuracy of plantar region extraction was assessed by comparing 50 plantar images extracted by the proposed method (**Figure 4a**: PM) and manually (**Figure 4b**: Ground Truth, GM). Accuracy was assessed by absolute differences in false positive rate (FPR) and false negative rate (FNR). FPR is defined as over-capturing rate above the true value (Equation 1), while FNR is under-capturing rate (Equation 2). We found that the FPR and FNR were 20.3% and 5.9%. We consider that the rates are sufficient to calculate positional information.

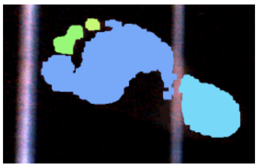
$$\mathrm{FPR} = \frac{\mathrm{PM\ w/o\ GT}}{\mathrm{GT}} \times 100 \tag{1}$$

$$\mathrm{FNR} = \frac{\mathrm{PM\ w/\ GT}}{\mathrm{GT}} \times 100 \tag{2}$$

2.3 Positional information

2.3.1 Conversion coefficient, P2M

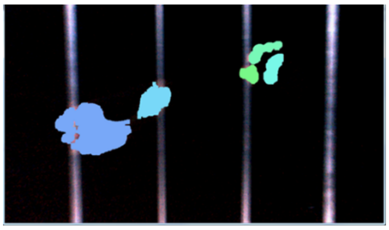
The positional information of the foot of the person walking on



(a) Normal plantar divided by the line

(b) Flat arch

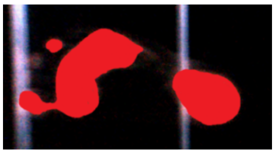
(c) High arch



(d) Detection of 2 soles in 1 frame

Fig. 3 The expanded plantar regions.

(a)



(b)

Fig. 4 Calculation of the extraction accuracy of the proposed method by comparing (a) plantar image extracted by the proposed method (PM) and (b) plantar image extracted manually (Ground Truth, GM).

the CaTTaP is obtained by calculating the coordinates of the extracted plantar regions.

To calculate positional information, the coordinates (pixel) should be converted to accurate positions (mm). To calculate the ratio of pixel-mm (*P2M*), we measured the number of the diagonal length of a captured image of A4 paper and compare it with the real size (363.7 mm). As a result, *P2M* was calculated to be 0.528. As the camera of the CaTTaP was fixed, *P2M* did not change. Therefore, *P2M* was defined as 0.528 mm/pixel in this study, and this value was used in the calculation.

2.3.2 Accuracy of object detection

The first preliminary test was conducted to estimate the accuracy of object detection in various positions of the capturing area. A paper printed with 9 circles, each 5 cm in diameter (close to the size of the heel), was placed on the walking surface of the CaTTaP. The 9 circles on the paper were captured by a camera and detected by image processing. The diameter of each detected circle and the true value were compared by calculating using the following equations:

$$\%\ \text{error} = \left|\frac{\text{truth value} - \text{measured value}}{\text{truth value}}\right| \times 100 \qquad (3)$$

The average percent error was 2.6%, the maximum error was 3.6%, and the minimum error was 0.1%. As mentioned in section 2.1, to measure the variation in step length, the error has to be less than 5%. Therefore the accuracy of object detection in various positions of the capturing area is adequate to evaluate human gait.

2.3.3 Reproducibility

The second preliminary test was conducted to estimate the reproducibility of object detection. A paper printed with 1 circle was captured 5 times at intervals of 5 seconds under the same condition. The captured images were processed to calculate the diameter. The diameter of each image and the true value were compared by calculating % error (Equation 3). The average percent error was 0.034%, the maximum error was 0.049%, and the minimum error was 0.007%. As mentioned in section 2.1, to measure the variation in step length, the error has to be less than 5%. Therefore the reproducibility is adequate to evaluate human gait.

3. Experiment (Step length and width)

Using the positional information, we measured step length and step width that cannot be calculated by a conventional treadmill. For this study, we recruited 6 robust elderly persons (hereinafter referred to as subjects a–f; mean age: 71.3 years; mean height: 161.9 cm; mean weight: 66.4 kg). The study was approved by the Ethics Committee of Tokyo University of Science. The test procedures and possible risks were explained to each subject prior to obtaining written informed consent. We conducted measurements at 3 walking velocities: the most comfortable velocity, velocity higher than comfortable walking velocity by 0.5 km/h, and velocity lower than comfortable walking velocity by 0.5 km/h (hereinafter referred to as low, normal, and high velocity). Normal velocity for each subject was determined by walking at various velocities on a treadmill before the experiment. The CaTTaP captured 1,000 frames and obtained continuous plantar images for 20–40 steps in each trial (time: 16.6 s/trial). The capture area was sufficiently large to capture the soles during a walk. However, at the edge of the image, calculation accuracy may be lowered by distortion correction of the camera. Therefore subjects were instructed to walk in the center of the treadmill and looking straight ahead as much as possible before images were captured. Until just before the experiment, the subjects were instructed to practice walking on the treadmill for 1 minute. To evaluate the accuracy of the proposed method, we measured the step length and width by the proposed method and by a motion capture system (MCS) with 6 cameras (OptiTrack, FLEX: V100R2, 100 fps, 3D accuracy: less than 1 mm) at the same time. The swing phase was most clearly captured. Thus the step length and width were calculated by the positional information of tip of the toe in the pre-swing phase using the following equations:

$$SL_i = (X_i - X_{i+1}) \times P2M + T_i \times S \qquad (4)$$

$$SW_i = |Y_i - Y_{i+1}| \times P2M \qquad (5)$$

$$T_i = \sum_{I_i}^{I_{i+1}} \text{frame time} \qquad (6)$$

Equation 4 shows the calculation of the step length [*SL* (mm)] from the plantar region of the coordinate on the sagittal axis [*X* (pixel), as shown in **Figure 2h**] of No. i step and No. i+1 step. S (mm/s) is the rolling velocity of the CaTTaP. Equation 5 shows the calculation of the step width [SW (mm)] from the plantar region on the transverse axis (Y (pixel), as shown in **Figure 2h**). Equation 6 shows calculation of the step time [T (s)] from the total frame processing time [*frame time* (s)]. The image number is shown as I. Using the MCS, step length and step width were calculated from the positions of the markers placed on the 2nd metatarsal bone in the pre-swing phase, the step time and the rolling velocity. **Figures 5** shows the box and whiskers plot for measurement accuracy, depicting the range of variation of the absolute values of differences (absolute differences) between the results obtained using the proposed method and the measurements obtained by the MCS as true values, for each subject and for each walking velocity. In the box plot, the blue rectangle spans the first quartile to the median of the absolute difference; the green rectangle spans the median to the third quartile of the absolute difference. The line separating the blue and green rectangles is the median and "whiskers" above and below the box show the minimum and maximum absolute differences. **Figure 5a and c** shows that the variability of the absolute differences differs significantly among subjects. **Figure 5b and d** shows that variability of the absolute differences is not significantly different among walking velocities.

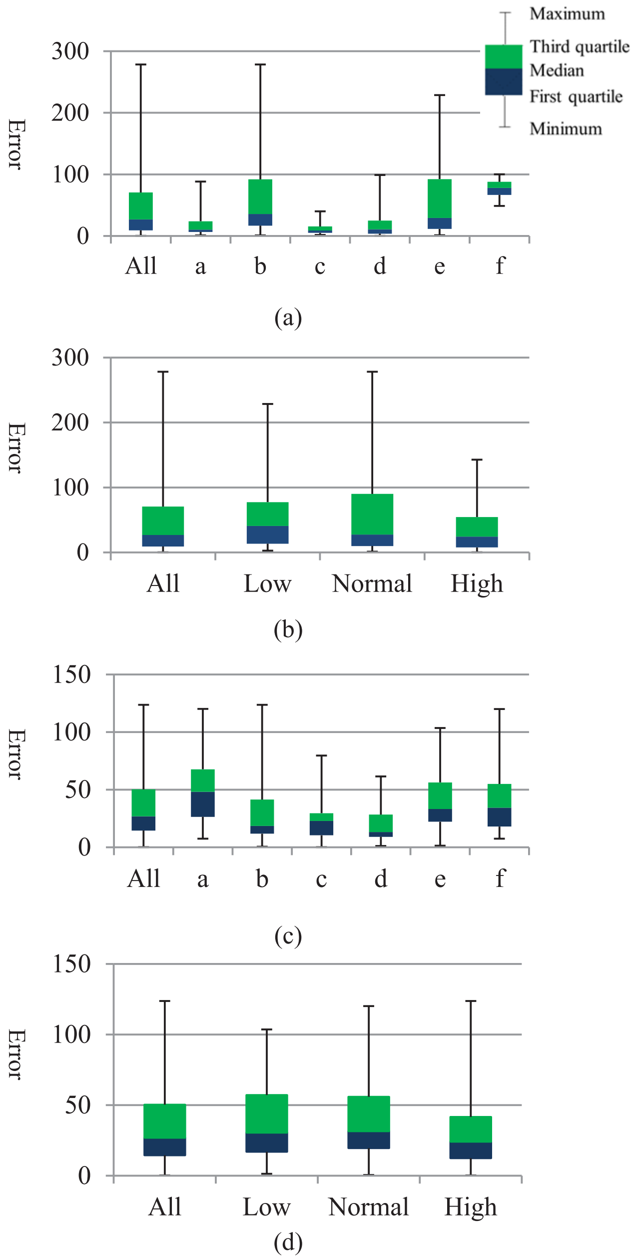
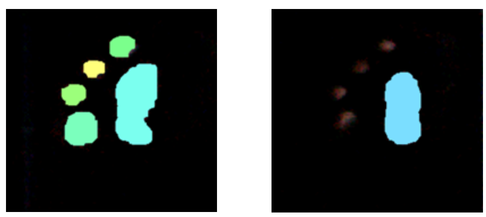


Fig. 5 Measurement accuracy. Figure 5a shows accuracy of step length for each subject. Figure 5b shows accuracy of step length for each walking velocity. Figure 5c shows accuracy of step width for each subject. Figure 5d shows accuracy of step width for each walking velocity.

4. Discussion

Comparison of absolute differences in step length and step width among various subjects and walking velocities showed that the accuracy varied depending on subjects (**Figure 5**). The higher accuracy group consisted of subjects a, c, and d, with low absolute differences both in step length and step width. In this group, the calculated errors for step length and width were less than 16.1 mm and 31.2 mm, respectively, and the entire sole was stably and steadily in ground contact from the heel to the toes during the initial swing phase as shown in **Figure 6a**. However, in the lower accuracy group, the calculated errors of step length and width were 61.2 mm and 34.4 mm, respectively, and the toes were sometimes off the ground in the initial swing phase, as shown in **Figure 6b**. The difference between toes on ground and toes off ground leads to errors of approximately 6% for step length and approximately 16% for step width. These findings suggest that consideration of ground contact of the toes may increase the accuracy of positional information.

In the majority of rehabilitation centers, step length is calculated by averaging the values measured manually for several steps. However, the variability of step length and width can be calculated automatically by the proposed method and other devices such as the motion capture system, accelerometer, and pressure plate. Kose et al. [15] estimated the measurement accuracy of step length by a tri-axial accelerometer. An IMU (FreeSense, SensorizeR) featuring a tri-axial accelerometer and two bi-axial gyroscopes (acceleration Resolution: 0.0096 m/s^2, Sampling rate: 100 frames/s) were used. A 10-camera BTSR SMART-D stereo-photogrammetric system (positional accuracy 0.3 mm) was used for validation purposes. The IMU was placed at pelvis level fixed to the subject's belt on the right side. The method was validated using measurements from the stereo-photogrammetric system as gold standard, in 9 walking subjects. For all subjects, the error of step length was estimated to be less than 3%. Webster et



(a) (b)

Fig. 6 The processed images of the toes in the pre-swing phase. Figure 6a shows the toes in ground contact. Figure 6b shows the toes off the ground.

al. [16] estimated the measurement accuracy of step length using an electronic walkway and the GAITRite system. The GAITRite system (GAITRite Gold, sampling rate: 80 Hz) comprises a series of sensor pads. The sensors are placed 1.27 cm apart (a total of 27,648 sensors) and are activated by mechanical pressure. The three-dimensional motion analysis system (Vicon-512, Oxford Metrics, 50 Hz) consisting of 6 cameras that track the movement of 25-mm markers attached to the subject's heel and toe was used for validation purposes. The error of left step length was estimated to be 3.4% and that of the right step length 2.9%. By our proposed system, the error of step length was estimated to be 3.8% error in the high accuracy group and 16.6% in the low accuracy group. The accuracy of the proposed system varies according to the type of gait, and the result from subjects who do not make ground contact with their toes during walking is low compared with the latest commercial devices. For clinical application, the precision of the image processing method requires improvement.

The proposed system has the following characteristic compared with a conventional system.

- Conventional devices capture the human plantar image as a static image only or the image for several steps. However, the CaTTaP is a treadmill; therefore the proposed system is able to capture clear images continuously during walking within a small space.
- Compared with conventional devices using data obtained by walking over paper with the soles covered in powder or by pressure sensors, the proposed system generates more precise plantar data. The conventional instrumented treadmill (Zebris FDM-T Treadmill) has 1 force sensor per cm^2, while the CaTTaP can capture 346 pixels per cm^2.
- Unlike the MCS or accelerometer system, no specific wear or device is required in our method, which shortens experiment time and reduces burden on subjects.
- The CaTTaP has a potential to calculate new parameters that cannot be measured using other devices, such as plantar contact area, plantar skin deformation, and shape of the sole. It is also possible to determine on/off ground of the toe, which is also difficult to estimate using other devices.

We conclude that CaTTaP is the best device for clinical measurement of gait from a new perspective.

5. Conclusion

This paper presents a new, simple system for human gait analysis that is easy to use by both patients and doctors. The proposed system uses the CaTTaP device to continuously measure gait parameters. In this paper, we only present the results of estimating the step length and width using the new system. The results indicate that the system should be improved further to obtain highly accuracy results. However, the CaTTaP has the potential to measure parameters such as the plantar contact area, plantar skin deformation, and shape of the sole, which are difficult to be measured by other devices. The CaTTaP also allows continuous acquisition of high resolution dynamic plantar images, and analysis of human gait. For clinical use, we are improving the system not only to analysis the gait of physically unimpaired person but also gait characteristics such as shuffle or floating toes. We believe that the CaTTaP is a simple but promising system for advanced gait measurements from a new perspective.

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