A Wearable Projector-based Gait Assistance System and its Application for Elderly People

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ABSTRACT
The ability to walk is particularly important to maintain a person's quality of life (QOL). In today's aged society, ways to support the impaired gait of elderly people with a decline in physical function is in great demand. This paper proposes wearable projector-based gait assistance as a novel application of mobile projectors. The technical challenge is to compensate the projected image with the intended position and size during walking. To verify the concept, we developed a self-gait training assistance system that displays stride length information on the floor while the user is walking. We conducted a study with ten healthy older adults (ages: 76–91). The results show the effectiveness of visual clues in controlling stride length and elderly people's acceptance of the wearable projector device.

Author Keywords
Wearable projector system, mobile projector, walking assistance, elderly person, self-gait training assist.

ACM Classification Keywords
H.5.1 Information Interfaces and Presentation: Artificial, augmented, and virtual realities.

INTRODUCTION
The ability to walk is particularly important to maintain a person's quality of life (QOL). However, a decline in muscular power, balancing ability or cognitive function of aging humans decreases their walking ability. Some health problems, such as Parkinson's disease and unilateral paralysis from a stroke [23], can also cause a disorder that affects walking. These declines of walking ability increase the risk of falls and subsequently result in fall-related injuries [5]. Preventing the decline is necessary for elderly people.

The various services intended to prevent elderly people from a decline in walking ability include manual gait training with a therapist, group exercise in a local community [13, 6], or gait training with large machinery such as a treadmill. Additionally, researchers in the clinical community are studying high-functioning and large-scale training systems with sensing technologies [34, 4]. A robotic suit that supports the human leg with actuators has also been developed for gait assistance [29]. However, senior citizens cannot fully benefit from these services and systems because the number of therapists is insufficient, and labor and specialized training equipment are still expensive. Due to these issues of gait assistance in today's aged society, a practical way to assist the walking of elderly people effectively and at low cost is in demand. One of the most promising approaches is mobile gait assistance with information presentation.

In this paper, we deal with mobile gait assistance for elderly people; specifically, a wearable mobile projector system is investigated. The mobile projector has come under the spotlight as a personal device to support a wide range of user tasks due to its improved performance as well as its reduction in size and weight [16, 1, 7, 15]. The adoption of a wearable mobile projector, however, is not merely due to its popularity and technical interest, but from the hypothesis that the information presentation method is safe and effective for elderly people. For example, a smartphone is one practical way to present information; however, most elderly people prefer to pay attention to their surroundings instead of a small screen. In the research community, a head-mounted display (HMD) is a popular mobile device for presenting visual information. In a video see-through HMD, the real-time information is overlapped with a video-captured image, and so the processing delay might cause VR sickness [27]. An optical see-through HMD, on the other hand, also requires the user to switch the focus of his or her gaze on the screen to watch the presented information. Moreover, auditory and tactile feedback can present supportive information [19, 11, 26]; however, these feedbacks largely limit the variety of assistive contents. For example, these feedbacks cannot present *spatial information*, such as "stride length" information, which has meaning at a specific position in the real world. We believe that a mobile projector-based system can overcome these limitations to realize various techniques of gait assistance for elderly people effectively and safely. To the best of our knowledge, no existing work on mobile projectors has investigated the support of gait training for elderly people. The contributions of the paper are four-fold:

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- Wearable projector-based gait assistance for elderly people is proposed as a novel application of mobile projectors.
- A floor projection technique, which compensates a projected image with an intended position and size during walking, is proposed as a core functionality.
- A self-gait training assistant system, which visualizes stride length during walking, is designed and implemented.
- A user study with ten elderly people (ages: 76-91) shows the potential of a mobile projector for gait assistance.

The rest of the paper is organized as follows. Related work is presented in the next section. The concept of wearable projector-based gait assistance and application scenarios are then described. A floor projection technique during walking is shown as a core functionality. A stride control system is implemented as an application and tested with ten older adults. We discuss the stride control system as well as the entire concept of wearable projector-based gait assistance. We finally conclude the paper by stating possible future work.

RELATED WORK

Due to the improvement of the performance and downsizing of a mobile projector, a number of Ubicomp researchers explored the potential of a mobile projector to support various user's tasks on the ground. McFarlane et al. [16] focused on military tasks such as mission briefing in a mobile team and verified that a wearable projector-camera system increased the performance of collaborative tasks. Pedestrian navigation is a popular application for a mobile projector because of users' familiarity with spatial information such as a route guide and the shareability with accompanying persons [1, 32, 33]. In contrast, we deal with gait assistance of elderly people as a novel application of a mobile projector.

Presenting information during walking imposes challenges of image instability and distortion depending on the type of information due to the fluctuation of the projector's posture. Winkler et al. [33] proposed the concept of turn-by-turn navigation for shoppers, in which navigational information, e.g., an arrow that indicates the direction to turn, is projected on the floor but the challenges are not identified. A projected arrow might be unstable during walking; however, we consider that such directional information without stabilization has little impact on comprehension. In contrast, as described later, our application scenarios are more spatially-aware than those in pedestrian navigation. It is important to take into account the physical dimensions of projected information: a user might not be able to adjust his/her stride unless the projected image is compensated.

Also, the style of carrying a projector has an impact on the severity of the challenge. Arning et al. [1] proposed a handheld projector-based pedestrian navigation system. Although the detail of their distortion-free projection is not presented, we consider that the challenge in instability and distortion of a projected image is smaller because of the nature of carrying a projector. In case of a handheld projector, a user holds a projector, as its name suggests, and intentionally projects information on the floor. This indicates that a user can adjust the posture of a projector to make the visibility of information suitable for him/her. However, this cannot be utilized in an application for elderly people for safety reasons. A projector consequently needs to be attached on an elderly user's body, i.e., a wearable projector, and the passive nature of the projector causes large fluctuation of the projector.

Image stabilization methods for wearable projector applications were proposed by Murata et al. [21, 22] and Tajimi et al. [30]. However, these methods cannot adjust the size of an image and resolve image distortion; they can only stabilize the image projection against the fluctuation of a projector. Moreover, Dao et al. [3] only focused on the correction of image distortion. In contrast, our proposed projection compensation algorithm aims at projection with an intended size, correction of image distortion, and projection stabilization during walking. This would enhance the versatility of wearable projector-based applications.

WEARABLE PROJECTOR-BASED GAIT ASSISTANCE

In this section, we present the concept and the applications of gait assistance with a wearable projector.

System Overview

Figure 1 illustrates the concept of a wearable projector-based gait assistance system, which consists of wearable sensors, a mobile projector and a processing unit. The wearable sensors can include an accelerometer, a heel switch, a heart beat sensor, an electromyograph (EMG), and so on. The system then generates gait assistive information based on gait parameters and projects the information on the floor as the user is walking. Note that sensors and projected contents vary depending on the person or the purpose of training.

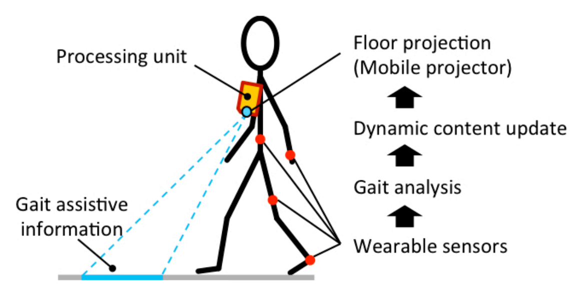

Figure 1. Overview of wearable projector-based gait assistance.

Application Scenarios

We show three classes of applications to derive the functional requirements for the floor projection technique.

(a) Self-gait training assistance for elderly people

The first application aims at supporting self-gait training to maintain the walking ability of elderly people who need preventive care. In other words, prospective users are people whose walking ability might decline in the future, even though they are currently able to walk without assistance. The system provides them with instructions to bring them close to the ideal gait by projecting assistive information, e.g., stride length (Figure 2 (a)), or the balance of the center of mass or the angle of the toe/ heel, based on their walking abilities. We focus on this class of application and show a concrete implementation, followed by a user study.

(b) Gait disorder relief for patients with Parkinson's disease
A number of patients with Parkinson's disease have freezing of gait (FOG) that makes it difficult to start walking or a senile gait that makes the stride shorter. These gait impairments can be controlled by visual stimuli such as placing vinyl tape and sticks on the floor, e.g., [31]. Our system projects a colored line that imitates vinyl tape (Figure 2 (b)) or a stick placed on the floor so that the Parkinson's gait disorder can be alleviated on demand.

(c) Highlighted projection on obstacles for preventing a fall
Elderly people with attention deficit disorder (ADD) or hemiplegic patients tend to stumble on slightly uneven surfaces or on common obstacles, such as a newspaper, a magazine or an electrical cord. The user can be alerted about obstacles on the floor to avoid falling during walking. The system may detect such obstacles by using a RGB/RGBD camera or a laser range finder. The system highlights the obstacle by projecting a spotlight (Figure 2 (c)). Auditory or vibratory feedback can also alert the user about the existence of obstacles; however, we consider that a visual stimulus by direct projection issues a stronger alert.

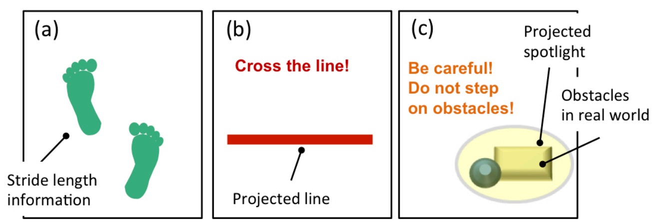

Figure 2. Three types of gait assistance: (a) a visual aid reflecting the user's gait, (b) visual clue that imitates vinyl tape stretched on the floor for relieving Parkinson's gait impairment, and (c) projected spotlight to highlight obstacles that can cause falls for elderly people with ADD or hemiplegic patients.

FLOOR PROJECTION TECHNIQUE

We describe the floor projection technique as a core functionality of the wearable projector-based gait assistance.

Functional Requirements

By analyzing the characteristics of the above applications, we identified the following functional requirements for an information projection system:

- Projecting an image to an *intended position* in the real-world coordinate system
- Projecting an image with an *intended size* in the real-world coordinate system
- Correcting an *image distortion* on the floor

The contents in gait assistance range from simple text messages and pictures to *spatial information*. Spatial information is meaningful in real-world coordinates. In the previous application examples, the stride information in (a), the visual cue that imitates vinyl tape stretched on the floor in (b), and the spotlight projection for highlighting obstacles in (c) are spatial information. These assistive contents have no meaning unless an image of a specified size is projected to the target position in the real-world coordinate system. The fluctuation of the projector posture due to body sway during walking complicates the contents. The projected position and the size of the projected image are displaced on the floor depending on the projector posture. Therefore, the first and the second requirements are specified. Furthermore, the angle between the light source of the projector and the projection surface, i.e., the floor, causes image distortion. The image distortion not only decreases the viewability of projected contents but also negates the meaning of spatial information, which leads to the third requirement. These projection compensation functionalities help to project an image to a target position with an intended shape, i.e., the specified size without distortion.

Key Decisions in Projection Compensation

We describe the key decisions in designing the projection compensation method.

Hardware- vs. software-based
Projection compensation is realized in two general ways: hardware-based and software-based. In the hardware-based approach, the direction of the projector light source is mechanically controlled by an actuator [18]. The approach allows precise compensation of the position of projection; however, the wearable device is likely to be heavier and larger. Moreover, physical control of the actuator might involve a delay. In contrast, a software-based method based on image processing does not need such an external device. Hence, we used a software-based method due to its superior wearability in the gait assistance of elderly people.

Environment-aided vs. self-contained
The software-based approach controls the position or the shape of the image in the projector coordinate system. In this approach, it is essential to estimate the projector posture against the projection surface. The estimation is classified into two types: estimating absolutely by a clue embedded in the environment, and estimating relatively by an on-board sensor. The environment-aided approach is realized by a wireless tag embedded in the environment [25] or a special surface with embedded light sensors [12]. The approach limits the utilization of a system to a specific area, which might become a drawback for the gait assistance of elderly people. In contrast, the sensor-based projection compensation is a self-contained approach based on posture measurement by an inertial sensor [30] or a motion sensor [3]. This allows the user to utilize the system anywhere he/she wants. Therefore, we took the inertial sensor approach.

Projection Compensation Algorithm with Inertial Sensor

Algorithm overview
The proposed projection compensation method calculates four vertices in the projector coordinate system based on the current projector posture and the projection condition, i.e., the position and the size of the target image. The perspective transformation is then applied to the original image. Dao et al. [3] only focused on the correction of image distortion, while Tajimi et al. [30] proposed projected image compensation in moving states. In contrast, our approach takes into account not only the position of projection but also the size of an image and the distortion for spatial information presentation in the real world.

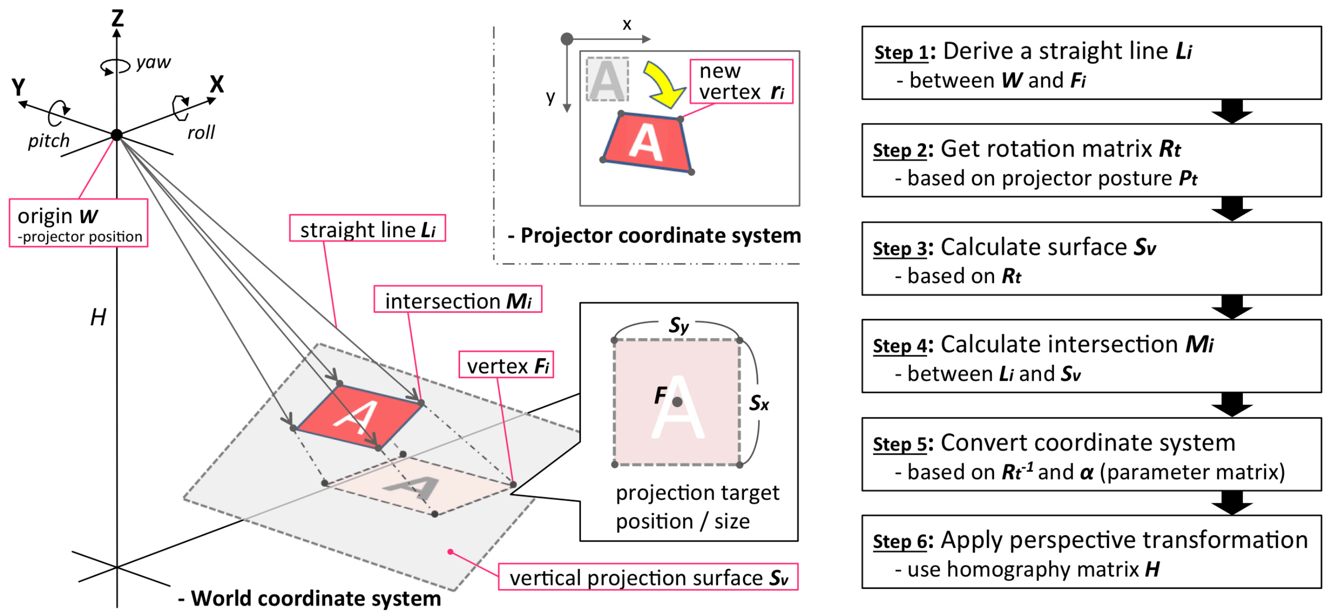

Figure 3. Coordinate system definition of projection compensation algorithm (left) and processing flow of our proposed algorithm (right).

Coordinate system

Figure 3 (left) shows the definition of the coordinate system in the proposed method. We assume that a user walks with a projector (height: H [cm]), and the projector light source is defined as the world coordinate origin $W(0, 0, 0)$. Two projection conditions, which are the target image position $F(X, Y, -H)$ and the image size (S_x, S_y) [cm], are also given by the application. The four vertices of the target projected image are represented as F_i.

Procedure

The detailed procedure is described based on the right part of Figure 3, in which we focus on one of the vertices F_i. The four output vertices that satisfy the three conditions of projection position, image size and distortion-free image, are obtained by applying Steps 1 to 5 to each vertex (F_0–F_3). Step 6 is the perspective transformation to obtain the compensated image.

Step 1: A straight line L_i between W and F_i is derived by calculating a unit vector $\vec{E}$ of vector $\vec{V}$. The unit vector $\vec{E} = (e_x, e_y, e_z)$ is obtained based on vector $\vec{V} = (X_i, Y_i, -H) = (v_x, v_y, v_z)$ that directs to F_i from W, as shown in equation (1). Here, l is the norm of $\vec{V}$.

$$\vec{E} = \left(\frac{v_x}{l}, \frac{v_y}{l}, \frac{v_z}{l}\right) \tag{1}$$

Step 2: The current posture of projector P_t $(roll, pitch, yaw)$ is estimated by inertial sensor data, and the rotation matrix R_t is calculated from P_t.

Step 3: The vertical projection surface S_v (equation (3)) is defined as the plane that rotates the YZ plane at X=D_t by matrix R_t. D_t (equation (2)) represents the distance from W to the center point of projected surface S_v, where p_p is the pitch angle. Constants a, b, c and d are calculated based on the relationship between S_v and its normal vector $\vec{n}$.

$$D_t = \frac{H}{\cos(90 - p_p)} \tag{2}$$

$$aX + bY + cZ + d = 0 \tag{3}$$

Step 4: The intersection point $M_i(X_{mi}, Y_{mi}, Z_{mi})$ between line L_i and surface S_v is obtained. Any point Q that exists on L_i at distance k from W is represented as equation (4). The condition in the case that Q is on S_v is shown by equation (5). Constant k is then calculated from equation (5), and M_i is derived by substituting k into equation (4).

$$\begin{aligned} Q &= W + k \cdot \vec{E} \\ &= (k \cdot e_x, k \cdot e_y, k \cdot e_z) \end{aligned} \tag{4}$$

$$a(k \cdot e_x) + b(k \cdot e_y) + c(k \cdot e_z) + d = 0 \tag{5}$$

Step 5: To transform the coordinate system, M_i is rotated by R_t^{-1}, and M_i' is obtained. $M_i'(X_{mi}', Y_{mi}', Z_{mi}')$ is a point in the YZ plane at $X = D_t$ (equation (6)). Then, a new vertex r_i is calculated by multiplying variables of M_i' with the projector parameter matrix α^{-1} (equation (7)). Putting a point at the r_i coordinates means that the point is projected to F_i in the world coordinate system. The scalar matrix α, which depends on the resolution of the display and the angle of projection, transforms the coordinate system. We obtained α in a preliminary experiment.

$$M_i' = R_t^{-1} \cdot M_i \tag{6}$$

$$\begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} = \alpha^{-1} \cdot \begin{bmatrix} Y_{mi}' \\ Z_{mi}' \\ 1 \end{bmatrix} \tag{7}$$

Step 6: In the final step, the perspective transformation is applied to the original image in the projector coordinate system (equation (8)), which is realized by homography H. Here, H is a parameter matrix that characterizes the transformation and is defined by the four point correspondences.

$$\begin{bmatrix} x_i' \\ y_i' \\ 1 \end{bmatrix} = H \cdot \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} \tag{8}$$

AN APPLICATION: STRIDE CONTROL FOR SELF-GAIT TRAINING ASSISTANCE

We used the application of (a) in Figure 2 as a pilot study and developed a stride controlling system.

Application Overview

Preventive care has become an important goal in our aged society. This pilot study focuses on the "length of stride." A person's length of stride gradually decreases with age because of the decline of the lower limb muscles or the weakened balance, which increases the risk of falls and subsequently can cause the person to be bedridden. Therefore, lengthening the stride of elderly people has a significant role in maintaining their QOL. The proposed system controls the length of the stride by presenting visual clues on the floor so that the user can maintain the appropriate stride during walking. The user walks while interacting with the visual information; consequently, the length of his/her step is controlled. This system targets healthy older adults who need preventive care for their anticipated decline of walking ability. Note that, for simplicity, we assume that clinical experts such as physiotherapists register the length of a person's stride based on his/her walking ability. An adaptive stride length setting is on the agenda for future investigation.

Designing the Stride Controlling System

Stride visualization

Two types of stride visualization are considered regarding the interaction with projected information (Figure 4): (a) step-type and (b) prediction-type. The step-type provides the user with an indicator for the next position of a step. The user walks by stepping on the foot-shaped image. In contrast, the prediction-type visualizes the positions of the second and third steps. The user determines the next stride length from the positional relationship between the visualized second and third steps. The user might feel as if he/she were viewing the footmarks of an *invisible person* who always walks one step ahead. To realize these stride visualizations, the following functionalities are required:

- Walking speed estimation
- Position determination for stride image presentation
- Heel contact detection and left/right step image switching

Walking speed estimation

Walking speed must be considered to realize the two visualization patterns. This means that the projected position of a step is updated continuously by taking into account the user's speed. The user cannot step on a stride indicator unless the projected position of the image is adjusted based on his/her walking speed in (a). Thus, real-time estimation of the walking speed helps to intuitively regulate the length of the user's step.

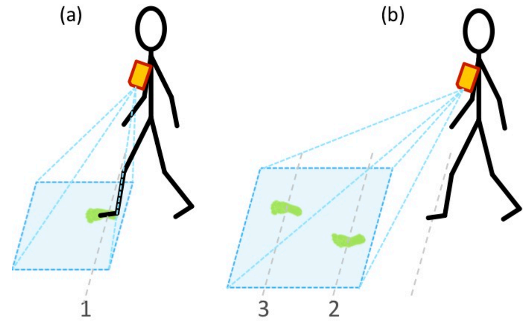

Figure 4. Visualization of stride assistant information. (a) Step-type: a stride indicator for the next step and (b) prediction-type: footmark information to predict user's own stride.

The potential of a regression model to estimate the walking speed or distance was reported in the literature [9, 14, 20, 28]. We adopt the linear regression model as the simplest form, represented as "$v = a \cdot f + b$" (v: speed, f: gait feature variable, a and b: user-dependent constants). Here, the gait feature suitable for elderly people is investigated. We specify the gait feature based on a preliminary experiment in a later section.

Position determination for stride image presentation

The position of stride image F in the projection compensation algorithm is calculated by walking speed v. F is represented as $(n \cdot SL - v_t \cdot \Delta t, Y_{L/R}, -H)$. The system then applies the projected image compensation algorithm by using F. Consequently, a new stride image is rendered on the floor. Note that SL and Δt indicate the length of the stride and the processing interval, respectively. Also, n represents the order of the step projected on the floor, where n=1 for (a) step-type and n=2 or 3 for (b) prediction-type projection.

Heel contact detection and stride image switching

The system also needs to detect heel contact events during walking as a trigger for switching the images of the left/right steps and resetting the projected position F. Two types of methods can be considered for the detection of a heel contact event: acceleration-based and force sensor-based. An acceleration-based approach, however, has a problem with detection accuracy, although accuracy detection might be realized by an accelerometer in a smartphone. In contrast, a force sensor-based approach can detect the events accurately, given that the force sensor is installed in the user's shoes. Considering the detection accuracy in our user study, we took the force sensor-based approach.

System Architecture

Based on the system model of wearable projector-based gait assistance (see Figure 1), concrete system components for the stride controlling system are defined in Figure 5. The components are the Processing Unit, the Heel Contact Detector consisting of two heel contact detection units (left/right), the Mobile Projector and the Inertial Sensor. The Processing Unit is divided into two parts: the Application and the

Projection Compensation Functionality parts. In the application part, the projection condition (position and size) is calculated based on a heel contact event from the Heel Contact Detector. In the other part, the Projection Compensation Functionality obtains the compensated vertices from the projection condition and the posture of the projector.

The Heel Contact Detector sends a contact event to the Stride Image Switcher and the Speed Estimator. The Stride Image Switcher determines the side of the foot to show as an appropriate image, while the Speed Estimator estimates the walking speed, as described above, based on the signal from the two shoe-mounted modules. Then, the Step Position Determinant calculates a new projection position. The Image Renderer passes the projection condition to the Output Vertices Calculator to obtain the four output vertices. The Output Vertices Calculator applies the Projection Compensation Model with the projector's posture information from the Projector Posture Estimator. The projector posture is estimated by the combination of a gyro sensor and an accelerometer. An absolute posture is estimated from the acceleration data during rest, and the difference obtained by integration of the gyro data during walking is incremented. The projector finally presents the compensated image transformed from the original image by the Image Renderer.

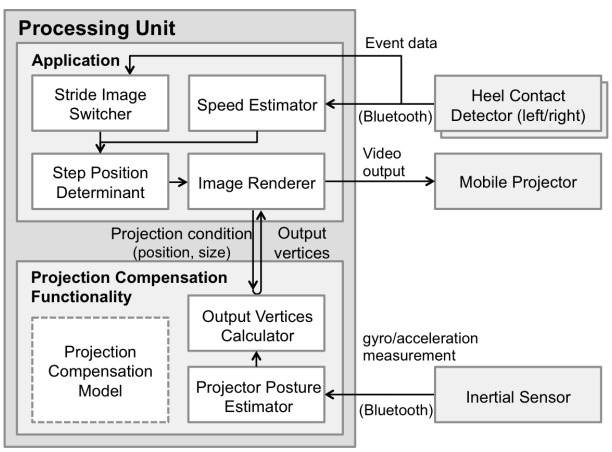

Figure 5. System architecture.

Implementation

All the components of the processing unit were implemented in a commercial smartphone. Particularly, the projection compensation functionality was implemented as a Java library for Android OS, which accelerates the development of the wearable projector-based gait assistance system. In this section, we describe the parameter fitting and the system configuration.

Walking speed estimation

Several gait features are proposed in the literature to estimate walking speed in the regression model: acceleration [9], step cycle (frequency) [20, 14], and a hybrid method [28]. We examined three features: 1) vertical acceleration difference ($max - min$) [9], 2) forward acceleration difference ($max - min$) [9], and 3) step frequency [20, 14]. A preliminary experiment was conducted with ten older adults to find the best gait feature. In this experiment, data were collected from two accelerometers (on the center of the patient's chest and waist) and two shoe-type wireless modules equipped with heel switches. Note that features 1) and 2) were measured by two accelerometers, which means five types of features were obtained for each subject. As a result of the multiple regression analysis with the five features, we found that the step frequency 3) contributed to the generation of the regression equation extremely well. Hence, we decided to use only the step frequency as the independent variable, and a linear regression equation was generated for each subject.

System configuration

The configuration of the stride controlling system is shown in Figure 6. The mobile projector (SHOWWX+ (HDMI Edition, 848×480 pixels, 15 lm), Microvision Inc.) uses a laser as the light source, and so the focal distance does not need to be adjusted. The smartphone (Droid RAZR (ARM Cortex-A9 1.2 [GHz] Dual Core Processor, Android OS 2.3.6), Motorola Inc.) performs all the processing of the stride controlling system. The smartphone outputs the video signal to the mobile projector via HDMI. The inertial sensor device (WAA010, ATR Promotions Inc.) containing the accelerometer and gyroscope was attached to the projector, and the accelerometer and gyroscope measurements were used as the posture data of the projector. The sensor device transmitted the measurements to the smartphone over Bluetooth. The user wore the projector device shown in Figure 6 at the center of his/her chest, with a neck strap and a band for fixing the device. A compact mirror was attached to adjust the projection angle manually because of the variations of postures of each elderly person, such as the forward-bent posture often seen. The total weight of the wearable projector device was 285 [g].

A wireless sensor module was mounted on the heel of each shoe to detect the user's heel contact. The wireless sensor module consisted of the micro-controller (Arduino Pro Mini, ATmega168 (8 [MHz])), a Bluetooth module, a force-sensitive resistor and a lithium polymer battery. The force-sensitive resistor was put inside the heel of the shoe for clear contact detection, and the contact events were sent to the smartphone over Bluetooth. All of these components are available from electronic parts shops such as SparkFun Electronics Inc.

USER STUDY

A user study was conducted to assess the feasibility of the stride controlling system. Specifically, the following points were evaluated:

- Effectiveness of the visual clue in controlling the stride length
- Influence of the stride projection on the gait
- Acceptability of the wearable projector device

Methodology

The experimental settings and procedures are described in this section. The experiment was conducted in January and May 2013 with the abovementioned ten healthy older adults (eight females and two males, ages: 76–91), who could walk

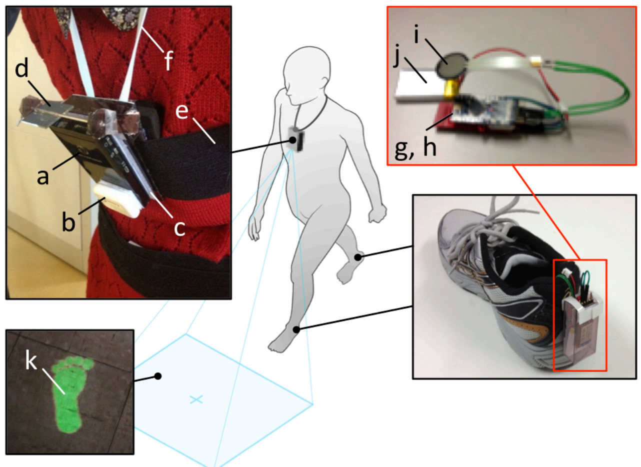

Figure 6. System configuration of the stride controlling system. (a) mobile projector, (b) inertial sensor (accelerometer + gyroscope), (c) Android smartphone, (d) mirror, (e) band for fixing, (f) neck strap, (g, h) Arduino Pro Mini + Bluetooth module, (i) force-sensitive resistor, (j) lithium polymer battery and (k) stride image.

without assistance. The subjects, who were recruited at the Kojiya hospital and at an elderly residential community in Tokyo, participated under the supervision of a physiotherapist.

We verified whether the subject's step was controlled by the projected visual clues. Figure 7 shows the flow of the experiment. First, the experimenter explained the purpose of the experiment to the subject, who wore the projector device and accelerometer (TSDN121, sampling rate: 50 [Hz]) at the center of his or her waist. The accelerometer was used for the analysis and to calculate the gait indices, described later. Then, for four times, the subject walked 8 meters straight, excluding a 1 [m] acceleration path and a 1 [m] slowdown path to collect baseline data. We recorded the number of steps and the waist accelerations during walking. The experimenter instructed the subject to walk as quickly as possible. The target stride length of the subject was determined by the number of steps in the baseline walking. Note that we set 8 meters of net walking distance, because this is a typical distance used at Japanese rehabilitative training facilities.

After determining the target stride length, the subject walked by following the projected stride information ($1+8+1$ [m], luminance: $50-75$ [lux]). The two patterns of stride visualization, (a) step-type and (b) prediction-type, were tested by dividing the ten subjects into two groups and assigning a different first pattern to avoid an order bias. Each subject walked four times under each pattern for a total of eight trials. The experimenter did not tell the target stride length to the subjects; instead, the subjects were asked "*Please walk by stepping on the foot-shaped image.*" in pattern (a) and "*Please walk according to the footmarks in front of you.*" in pattern (b). Note that at the beginning of each pattern, we set a warm-up time to get used to the equipment and walking.

Finally, in semi-structured interviews, the experimenter conducted questionnaire surveys about the projection of the stride information and the wearable projector device. The survey about the projection was intended to see the difference of the two types of presentations from the user's point of view. The subjective evaluation on the wearable projector device was conducted by the *Wearable Comfort Scale* (WCS) [8]. When a user wears a certain device, the level of comfort is affected by many factors. So, understanding the reasons for discomfort by comparing the rating on a single scale allows further improvement of the wearability of a device. WCS evaluates the wearable computing system for six factors: *emotion* about appearance and relaxation while wearing the device, *anxiety* about the safety and reliability of the device, physical feelings of the *attachment* of the device on the body, existence of *harm* in wearing, *perceived change* during wearing, and difficulty in *movement*. The subjects assessed our wearable projector device on a score from 0 to 10. Note that a lower score means a more ideal wearable device.

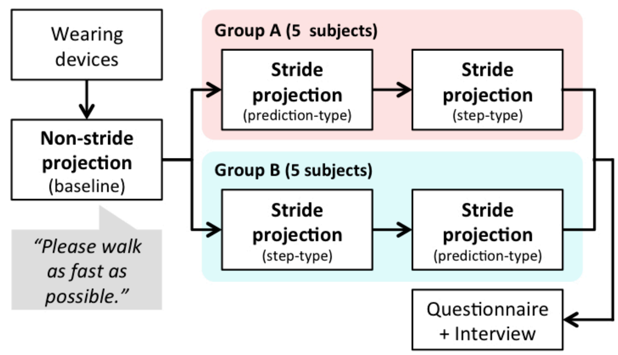

Figure 7. Flow of the user study.

Results

Accuracy of stride controlling

Table 1 shows the average stride length of each subject in the baseline walking and the two types of stride projection. The average stride length was obtained by dividing the walking distance (8 meters straight) by the average number of steps in four trials. The results show that the user's stride length was controlled by the projected visual clues with a mean absolute error (MAE) of 3.7% (pattern (a)) and 9.6% (pattern (b)). The accuracy of stride control differed according to the type of stride visualization.

Subject	Sex-Age	Baseline	Step-type	Prediction-type
S1	M - 80	52.0	53.3 (+2.5%)	46.4 (-10.8%)
S2	F - 85	45.0	43.2 (-3.9%)	39.6 (-12.1%)
S3	F - 91	40.0	37.6 (-6.0%)	36.3 (-9.2%)
S4	F - 83	27.0	26.7 (-1.2%)	28.2 (+4.4%)
S5	F - 76	55.0	52.5 (-4.5%)	49.2 (-10.5%)
S6	F - 82	47.0	45.6 (-3.0%)	42.7 (-9.1%)
S7	F - 87	46.0	43.7 (-5.0%)	41.9 (-8.9%)
S8	F - 80	40.0	41.1 (+2.8%)	35.1 (-12.3%)
S9	F - 76	39.0	41.5 (+6.4%)	34.4 (-11.8%)
S10	M - 76	56.0	55.1 (-1.6%)	52.3 (-6.6%)
MAE		–	**3.68%**	**9.57%**

Table 1. The accuracy of stride control [cm]. MAE: mean absolute error. The number in parentheses is the difference from the baseline.

Influence of stride projection on the gait

We analyzed the gait of subjects by two types of acceleration-based gait indices, *instability* and *regularity*, which were proposed in the clinical research field. Menz et al. [17] and Latt et al. [10] reported that gait *instability* was in proportion to the root mean square (RMS) of walking accelerations. Aucinet et al. [2] clarified that gait *regularity* was represented by the magnitude of the auto correlation during walking accelerations.

We randomly selected 256 acceleration samples (5.12 [sec]) on the three axes (x: walking direction, y: horizontal, z: vertical) recorded by the waist-mounted accelerometer to calculate the two gait indices. The gait indices of three axes were calculated in order to observe the influence of stride projection on the user's gait on each axis of the body. Figure 8 shows the ratios of the change of gait indices between the stride visualization pattern and the baseline stride for each subject (i.e., ratio = (gait index of step-type or prediction-type)/(gait index of baseline stride)). Here, the high ratio of the instability index (> 1.0) indicates that the gait is more unstable than the baseline, while the low ratio of the regularity index (< 1.0) indicates that the gait is more irregular than the baseline. We found that the step-type visualization tended to worsen the subject's gait ((a) and (c)). In contrast, we verified that the prediction-type visualization had less influence on the gait compared to the step-type ((b) and (d)).

Qualitative evaluation and interviews

Table 2 shows the results of the questionnaire regarding the contents of the stride projection. Regarding the visibility of the projected contents (the first question), all subjects answered that they perceived the projected image on the floor. We also asked about the perceived effectiveness of the projected instruction during walking. The results differed according to the visualization pattern. All subjects felt that they could walk by stepping on the projected step indicator; however, three subjects stated that they could not walk with the stride projection in the prediction-type. The results of the WCS questionnaire are shown in Figure 9, which indicates that the scores regarding physical wearability (attachment, harm, perceived change, and movement) were low, that is, ideal. In contrast, the scores of the psychological aspects (emotion and anxiety) varied among the subjects, and the scores were relatively high, that is, not ideal.

Question	Number of "*Yes*" answers	
Did you perceive the projected stride image?	10/10	
Were you able to walk based on the projected step?	Step-type	10/10
	Prediction-type	7/10

Table 2. Questionnaire results in the projected stride contents.

DISCUSSION

Characteristic of Two Stride Projection Patterns

As shown in Table 1, our system achieved control of the subjects' stride length with errors less than 10% from the baseline stride. However, the two types of visualization differ in the level of error: for the step-type, MAE=3.7% and for the prediction-type, MAE=9.6%. In the step-type visualization, the user could walk properly by stepping on the indicator because "stepping on the image" was a natural and intuitive motion for the user. In contrast, the prediction-type visualization forced the user to predict the next step position based on the positional relationship of the projected second and third steps. It might be difficult for elderly people to predict the next step because of the decline of cognitive capacity or sensory functionality with aging. These results are supported from the questionnaire results: two subjects (S2, S5 and S6) felt that they could not walk with the prediction-type. They answered that they had been confused whether they could walk in accordance with the invisible man's footmarks in the interview.

We also analyzed the gait influence of the two types of projection. The average instability rate of change in the step-type projection is 1.11% (worsening instability index) and the average regularity rate is 0.90% (worsening regularity index). Regarding the prediction-type projection, the average instability rate is 0.98% and the average regularity rate is 1.04%. Both indices barely improved. Step-type projection worsened the gait *instability* and *regularity* for most subjects. We consider that the results occurred for two main reasons. The first reason is the user's forward-bent posture, caused by stepping on the image projected in the near distance. This continual posture change might worsen the gait of the user. We also point out the inexperience of stepping on the image as the second reason. The gait of the user might get worse due to concentrating too much on stepping on the image, such that instability of the center of gravity occurred. The worsening gait indices of the y-axis are especially conspicuous. It is because the subjects tended to wait a short time before raising their legs to match the timing of stepping on the clue. The subjects tilted their bodies to the left and right and therefore altered the center of gravity balance. In contrast, we did not confirm the negative influence on the user's gait in the prediction-type projection. The characteristics of the two stride projection patterns are summarized in Table 3.

	Accuracy of Step Control	Influence on Gait
Step-type	High (MAE=3.7%)	Worsening gait
Prediction-type	Low (MAE=9.6%)	Less influence

Table 3. Summary of characteristics in two step projection patterns.

Suitability of Wearable Projector Device

The results of the WCS, which evaluated the device wearability, indicates high acceptability of the wearable projector device physically, i.e., movement, perceived change, harm and attachment. We also found that not all subjects accepted our wearable device from the psychological aspects, i.e., emotion and anxiety. This assumes that some subjects worried about how they looked when they wore the device and that they feared such an unknown device. S4, who rejected the device due to the psychological aspects, said in the interview, "*I hesitate to use this device in everyday life, although it is no problem to use when I conduct gait training in a hospital.*" To improve the emotional aspect, the design of the projector device should be refined from the psychological point of

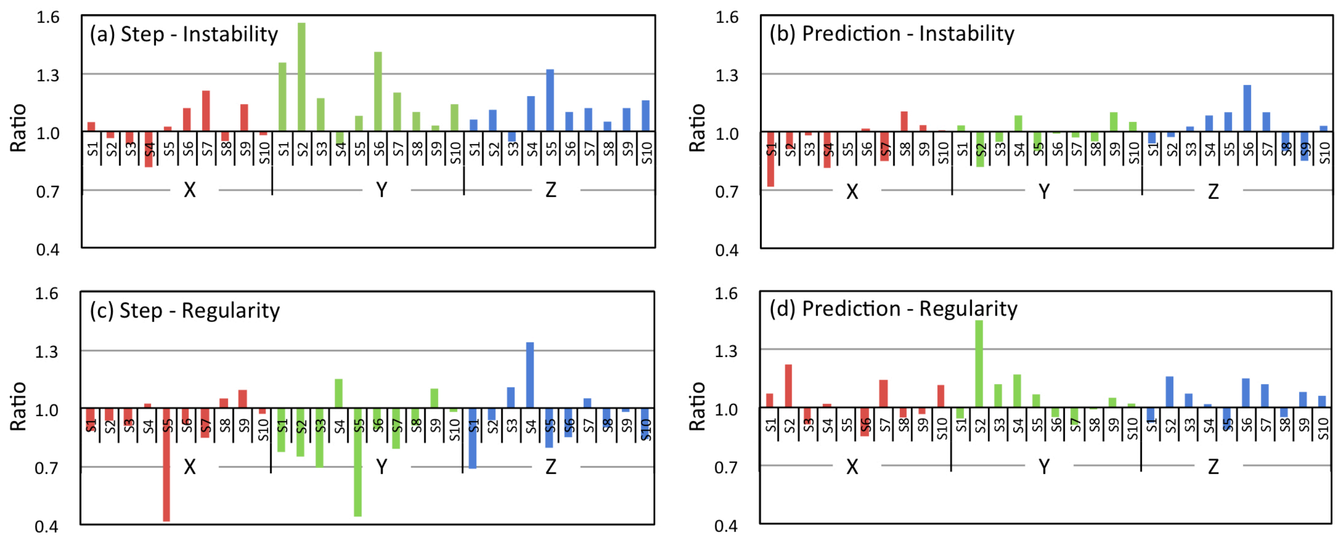

Figure 8. Results of gait index analysis, which show the rate of change of the gait index between the stride visualization and the baseline per subject and axis. (a) Instability rate of step-type, (b) Instability rate of prediction-type, (c) Regularity rate of step-type, (d) Regularity rate of prediction-type. Each horizontal axis indicates the subject's ID.

view. The anxiety aspect can be improved by sufficient explanation at a hospital and habituation effect. However, it is notable that the mobile projector device was accepted by elderly people in the physical aspects, although we first considered that to be a bigger issue because of the decline of the users' physical function or muscular power.

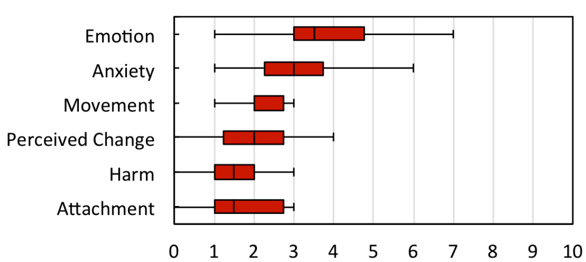

Figure 9. Results of WCS (Wearable Comfort Scale).

Feasibility of Self-gait Training with a Wearable Projector

The second author is a physiotherapist. Here, the feasibility of self-gait training with a wearable projector is discussed from the viewpoint of the physiotherapist. The results of the user study showed that step-type projection could increase the awareness of the user's own stride length because it is intuitive for elderly people; however, it might be difficult to utilize the visualization for a long period of time since the worsened gait might become a habit. Therefore, the prediction-type might be suitable for self-gait training because it has less impact on the elderly people's gait, although the control accuracy was slightly lower. Moreover, the characteristics of the two visualization patterns suggest that the combination of step-type and prediction-type projections might provide more effective training, since the step-type projection allows elderly people to control their stride length intuitively. In this hybrid training, the user usually would walk with the prediction-type stride projection, and, at regular time intervals, the user would walk with the step-type projection for a short time. These results indicate the feasibility of self-gait training assistance with a wearable projector system. However, the relationship between stride projection and falls has not been fully evaluated. We should clarify the safety aspect of the stride controlling system by an in-depth gait analysis.

Known Limitations of the Stride Controlling System

The stride controlling system currently has several limitations. The user cannot utilize the system in an outdoor environment. This is attributed to inadequate brightness of the mobile projector compared with that of natural sunlight. This not an inherent or unsolvable drawback of the proposed system. Hence, we presume that a user can carry out self-gait training with our system in indoor environments, such as the training room in hospitals or care facilities, or in a home hallway. We expect that the advancement of technology in the luminous intensity of projection would extend the scope of wearable projector-based self-gait training assistance.

We assume that clinical experts would register an appropriate length of stride length for each user's walking ability. To provide more fine-grained gait training assistance, the system should automatically determine the information. In the future, we will investigate a technique based on the accumulated gait logs of a user.

In the walking speed estimation by the linear regression model, walking speed v_n at the n^{th} step is calculated by utilizing walking frequency f_{n-1} at the $(n-1)^{th}$ step, that is, estimating the speed by the frequency data of the previous step. This means that the regression-based method cannot properly adapt to a dynamic speed change. Extreme examples are the beginning and ending of walking. This problem occurs in the application scenario (b) that aims at gait disorder relief of patients with Parkinson's disease. Such patients often cannot begin to walk due to gait impairment; therefore, visual cues that imitate vinyl tape must be projected at the beginning of walking. However, the regression-based model is not able to estimate the speed dynamically. Therefore, a dynamic speed change must be estimated in another way, such as estimating the displacement of the body by tracking the foot position with a RGB/RGBD camera.

CONCLUSION AND FUTURE WORK

As a new field for mobile projectors, we proposed gait assistance for self-training of elderly people using a wearable projector. A projection compensation technique was proposed as a core functionality. Here, an image is transformed and projected at the intended position and size on the floor when the user is walking. A stride controlling system was designed and implemented on an Android-based smartphone terminal. Through a user study with ten elderly subjects, we found the following:

- Visual clues projected by a wearable mobile projector could control the stride length of elderly people precisely.
- A wearable projector device was accepted by elderly people in terms of its physical aspects.

These findings imply that wearable projector-based gait assistance is practical for elderly people. In terms of technological aspects, we plan to conduct quantitative experiments to improve the projection compensation functionality, which includes reducing jitter of the projected image on the floor by applying a digital filter. Additionally, to improve the visibility of the projection, investigation of a method of automatically adapting to the floor pattern or color with a radiometric compensation technique [24] is under consideration. From an application point of view, we need to conduct an in-depth experiment to investigate the practical issues of a wearable projector-based gait assistance system. For example, we should evaluate the long-term effectiveness of stride controlling as well as investigate the relationship between stride projection and falling. A combination of another modality, such as audio and vibration, can be considered to allow safe gait-training by taking into account eye distraction. Additionally, we should clarify the effectiveness and acceptability of our system at different levels of decline in walking ability. Finally, other applications, as shown in Figure 2 (b) and (c), need to be developed and evaluated to validate the whole concept.

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