Clog-integrated plantar visualization system for evaluating activity during walking

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Abstract—**This study involves the development of a novel sensing system for the planta while walking on any surface and in any condition. In the study, the main aim is the visualization of the planta. A plantar image is reflected at the reflecting surface and captured by a camera embedded in a clog. The obtained visual information differs from the pressure and IMU data obtained from conventional sensors as it provides detailed information on the plantar surface. This is used to investigate the relationship between the activity in the toe area and stumbling experiences. The results indicate that high toe activity is associated with the group with no stumbling experiences and low toe activity is associated with the group with stumbling experiences.**

I. Introduction

The Cabinet Office of the Government of Japan [1] reported that falls are the fourth main reason for elderly individuals above 65 years of age to require support from caregivers. The demand for fall risk assessment to prevent falls increases along with aging. Several previous studies focused on this issue [2]–[8]. In this context, this study examines planter observation. A planter is a popular place for a self-health check in oriental medicine, and it is expected to reveal a significant amount of health-related information. However, a limited number of observation methods exist to obtain quantitative data. Plantar pressure is an extremely popular method [9] that is used to observe parts of the foot that are used by individuals while walking. However, this involves indirect observation and corresponds to a limited amount of obtained information. Examples of unobservable information by conventional indirect measurements include accurate contact area, skin deformation, and skin color. It should be noted that it is difficult to use pressure sensors to detect a contact area with low loads. Additionally, it is also difficult to identify the exact contact area using pressure sensors. Thus, the aim of this study involves visualization and direct observation of the planta. The main contributions include the following:

Wearable plantar visualization system: This study presents a novel plantar visualization system for direct observation of the planta. A transparent sole, a refraction mirror film, and a camera are embedded in a clog (shoe). The plantar image is reflected in the film and captured by the camera. The image reflection mechanism provides the thin sole with a thickness of 26 mm. When the clog is worn barefoot, the visualized planta is observable during any activity and while walking on any surface. The viewable area of the embedded camera is restricted to the planta, which means that privacy of the wearers is protected, and the physical and psychological burdens of the wearers are reduced. Thus, efficient and reliable data collection is expected. Passive joints are embedded at the camera holder and around tarsometatarsal joints such that individuals can walk normally while wearing the developed sensor clog. Size adjustable bands are also installed to deal with different sizes and foot shapes. A comfortable sensor clog with a plantar observation function is then realized.

Extraction of toe area activity: Visualization of the planta provides accurate information with respect to the contact area when compared to that of the insole pressure sensors. This information is utilized to investigate the relationship between the activity of the toe area and stumbling experience as a first step to evaluate the effectiveness of the proposed sensing system. The difference between the contact areas at the foot-strike and kicking phases is examined. The results indicated that the difference is associated with the extent to which the foot fingers rotate while walking, that is, the activity of the toe area. The experimental investigation reveals that the participants with a small difference possess experience of stumbling and vice versa.

The rest of this paper is organized as follows. The subsequent subsection describes related literature. This is followed by a discussion of the developed clog-integrated plantar visualization system. The experimental investigation is then presented in conjunction with the procedure to derive the activity of the toe area. Finally, the conclusion is discussed.

A. Related work

As discussed above, several studies focus on walking evaluation or gait analysis [2]–[8]. However, this section describes studies that focus on shoe-integrated walking measurement systems, which are closely related to the context of the present study [9]–[12]. Measurement systems are mainly classified into two types.

The first type corresponds to pressure sensor-based systems. There is an insole inside every shoe, and pressure

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profiles during walking can be obtained by embedding pressure sensors into the insole. There are several commercially available pressure sensors that are utilized to investigate the relationship between plantar pressure and walking speed [13] [14], ages [15], and foot type [16]. Majumder et al. [17] predicted falls by using sensory data from a smart phone and four pressure sensors on a shoe. Ayena et al. also [18] assessed the risk of falls at home with a system similar to that in the study by Majumder et al. [17]. Yu et al. [19] developed a shoe system that monitored walking with shoe-integrated force sensors. Crea et al. [20] developed a pressure-sensitive foot insole based on optoelectronic technology.

The second type of measurement systems corresponds to IMU (Inertial Measurement Unit) sensor-based systems [21]. Hung and Suh [22] reduced the position error of shoes estimated by IMU sensors by utilizing additional IR camera information. Do and Suh [23] developed a walking measurement system that utilized inertial sensors and a camera with floor markers to estimate step length and foot angle. An optical sensor was utilized although the targets did not correspond to a plantar observation. Foxlin [24] tracked pedestrians with shoe-mounted IMU sensors. Ojeda and Borenstein proposed a personal dead-reckoning navigation system with a shoe-mounted IMU sensor. Sim et al. [25] proposed an algorithm to detect falls with acceleration sensors on a shoe. Rampp et al. [26] estimated a stride parameter that utilized IMU sensors on a shoe. Mariani et al. [27] assessed the 3D spatial parameters of the gait with IMU sensors on a shoe.

There are also systems that involve both pressure and IMU sensors. Scheoers et al. [28] proposed an instrumented shoe with force and IMU sensors. Bamberg et al. [29] proposed a wireless wearable sensor system that included an accelerometer, a gyroscope, and a ground force reaction sensor that were embedded in a shoe. Bebek et al. [30] developed a personal navigation system with pressure and IMU sensors. Chen et al. [31] detected an abnormality with the shoes that included four force and IMU sensors. Hegde et al. [32] developed a shoe termed as the SmartStep shoe in which pressure and acceleration sensors were embedded. Kawsar et al. [33] presented an activity detection system that utilized pressure data from a shoe and smartphone data.

However, to the best of the authors' knowledge, most studies have not examined the development of a sensor shoe that utilizes visual sensors for plantar observation. The small space of a shoe sole makes it difficult to integrate visual sensors. Nevertheless, visual sensors provide the above-mentioned information that cannot be obtained with pressure and IMU sensors. This study focuses on this issue.

II. Clog-Integrated Plantar Visualization System

A. Design requirements

1. The planta is visually observable while walking
2. The system can be embedded in a clog and then worn.
3. The visible field is restricted to the planta.
4. The walking motion is not disturbed
5. The size can be adjusted according to the shape and size of the foot

The aim of this study includes developing an observation system that provides visual information related to the planta while walking. In order to realize the observation at any place and during any activity, it is necessary that the sensing system should be embedded in a clog and then worn. The visible field must be restricted to the planta to protect the privacy of wearers. Additionally, the system should not disturb the walking motion to observe plantar information. There are individual differences in the sizes and shapes of a foot, and thus size adjustable functions are preferable.

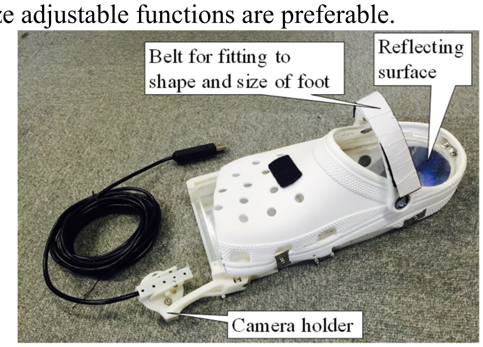


Figure 1. Clog-integrated plantar visualization system

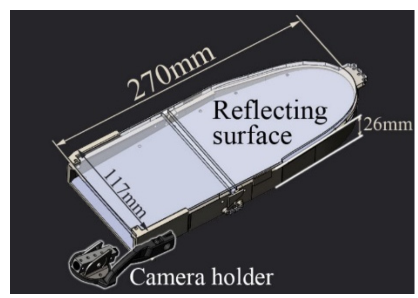
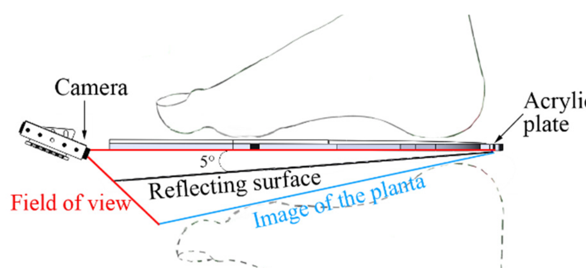
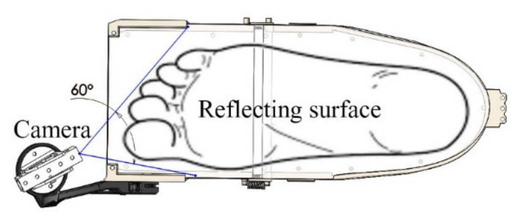


Figure 2. Underpart of the plantar observation system



(a) Side view of the sensing system



(b) Bottom view of the sensing system

Figure 3. A schematic illustration of the sensing system

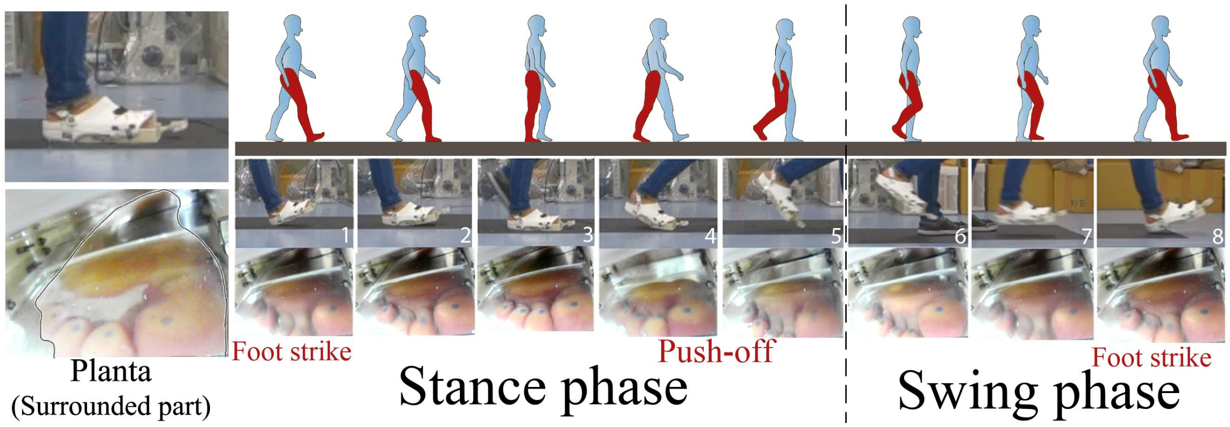


Figure 4. Definition of phases in a walking cycle and an example of an image obtained from the developed sensing system

B. Overview of the system

The sensing system shown in Fig. 1 is developed by considering the design requirements. A clog (Crocs) constitutes the base and constructs the upper area. Fig. 2 shows a schematic view of the underpart area and the main part for the sensing system that mainly consists of a reflecting surface and a camera. The image of the planta is reflected at the reflecting surface and is captured by the camera fixed at the holder.

C. Sensing system

Fig. 3 shows a schematic illustration of the sensing system. The camera is the fundamental sensor to obtain plantar visual information, and its position is important to observe the planta. The space under the insole is very low, and it is difficult to set a camera at the bottom of the clog and to directly capture the planta. For this setting, either a camera with an extremely wide field of view and extremely short focal length or multiple cameras are required. The utilization of only a single low cost camera is preferable from the viewpoints of low cost and system simplicity. The refracting surface is then set at the insole of the clog, and the reflected plantar image is captured by the camera at an external position (Fig. 3). The significant features of the developed system allow the observation of foot finger motions and acquisition of plantar surface information. The heel area of the foot is usually utilized only at the foot-strike phase and not at the push-off and swing phase (See Fig. 4 for the definition of the phases). Therefore, the primary observation target corresponds to the toe area of the planta, and especially the thumb that is necessary for the push-off motion. Hence, the camera (holder) position and the reflecting surface angle were determined in order to satisfy the following:

1) The image for the toe area and especially thumb is clear,

2) The image for the heel area is obtained at the foot-strike phase

3) The visible area is restricted to the plantar area.

An endoscopic camera (GIWOX; Resolution: 640 × 480, Focal length: 6 cm−infinite, Angle of view: 60°) with a short focal length is utilized to obtain a wide field of view. A reflecting film (with a thickness of 0.6 mm) is utilized such that the thickness of the reflecting surface is minimized and the thickness of the clog sole is close to the original thickness. Fig. 4 shows an example of the sequential images observed in a cycle of walking. It is observed that the toe area is visible at all phases while the heel area is visible at the foot-strike phase (The dark area in the figure corresponds to the heel area).

D. Walking facilitation system

Several walking facilitation systems are embedded and include the following:

1) Passive joints for rotating tarsometatarsal joints

The foot bends during walking and therefore elastic materials are utilized for the sole part of commercially available shoes. The developed system is solid to obtain stable refracted images. Passive joints are installed around the tarsometatarsal joints (Fig. 5) to minimize the stress on the solid part while walking and to allow natural foot bending. The maximum allowable joints corresponded to 40°. It should be noted that the heel area is not visible at the push-off phase owing to the passive joints.

2) Passive joint at the camera holder

The position of the camera holder is external to the clog, and it can disturb the walking motion during the push-off phase. A passive joint is installed at the root of the holder (Fig. 6) to minimize the effect. The camera holder then rotates according to the push-off motion at the push-off phase even though the heel area is not observable at the phase.

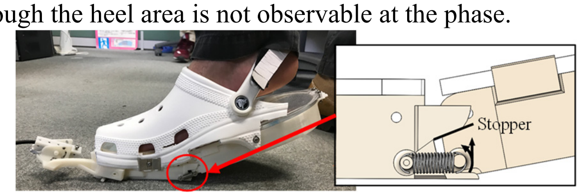


Figure 5. Passive joints to allow foot-bending around tarsometatarsal joints

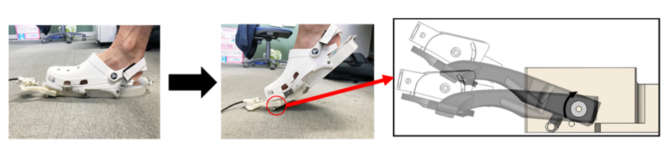


Figure 6. Passive joints at the camera holder

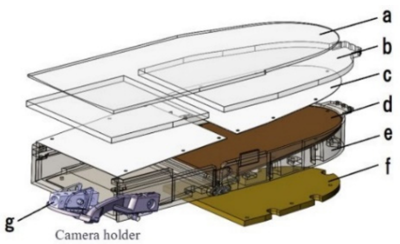


Figure 7. Structure of the clog-integrated plantar visualization system; a: Silicone plate, b: Acrylic plate, c: Cast coated paper (reflection film), d: Density Fiber board, e: Frame created by a 3D printer, f: Wood plate, and g: Camera holder

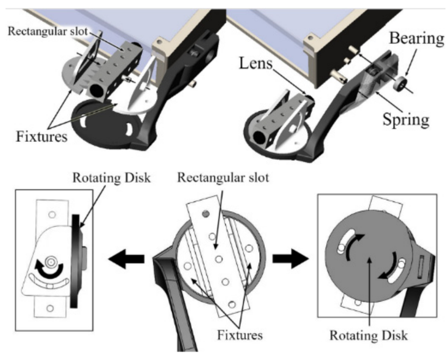


Figure 8. Structure of a camera holder

3) Adjustment of size and shape

Velcro (Fig. 1) is installed to allow the developed clog to fit according to the size and shape of the foot of a wearer.

E. Structure

The structure for all the parts of the system is shown in Fig. 7. It is assumed that the developed clog is worn on a bare foot. The silicone plate provides comfort and a good fit. The silicone and acrylic plates are transparent to enable visualization of the planta. The materials for the other parts are selected to support the weight of a wearer while minimizing the total weight of the clog. The connecting parts are manufactured by a 3D printer (uPrint SE).

Fig. 8 shows the structure of the camera holder. The direction of the fixed camera can be changed to fit the shape and size of the foot of a wearer. The main specifications of the developed sensor clog are shown in Table 1.

TABLE I. MAIN SPECIFICATIONS OF THE DEVELOPED SENSOR CLOG

Allowable foot size	$25 - 27$ cm
Allowable foot breadth	≤ 11 cm
Allowable instep height	$5 - 15$ cm
The size of the main part	$27 \times 11.7 \times 2.4$ (Sole thickness) cm
Visiblity of the toe area	Always
Visiblity of the heel area	Without the push-off phase

III. EXPERIMENTAL EVALUATION

Experiments are conducted to examine the effectiveness of the developed clog-integrated plantar visualization system. A main feature of the sensing system involves the capacity to observe the accurate contact area of the planta. The activity of a certain area can be estimated from the variation in its contact area. Based on this, we investigated the relationship between stumbling experiences and the activity of the toe area during walking, using the developed sensing system.

A. Participants

The participants are 8 young healthy individuals (7 men and 1 woman, age 22.4 ± 2.5 years, weight 62.1 ± 11.2 kg, height 166.8 ± 10.1 cm, foot size 24-27 cm) without any diseases, impediments, and medical history involving walking problems. The procedure and purpose of the experiments are approved by Medical Ethics Committee of Kanazawa University.

B. Procedure

The participants walked straight along a 6.5 m long flat road wearing the developed plantar sensing system on the right foot that includes a clog with a sole that has the same thickness as that of the sensing system on the left foot such that the difference in the sole thickness did not affect walking. The experiment is performed 3 times for each participant. We questioned the participants about their stumbling experience, and based on the experience, we separated the participants into two groups, which are, the group with no stumbling experience (5 individuals) and the group with stumbling experiences (3 individuals). The activities of the toe area are compared across the two groups.

C. Extraction of the activity of toe area

First, the toe area of the captured image is extracted at each frame. The activity of the toe area (that is the extent to which the participants moved their toe) is then evaluated.

The toe area is fixed with respect to the camera frame, and the toe area is then evaluated from the obtained image. Next, the contact area in the toe area is derived. The skin color of the bare foot provides information about contact and loading. The skin color turns white if the contact load is increased, and this is due to blocking of the blood flow inside capillary vessels. The whitened area then corresponds to the contact area. The contact area is extracted based on this concept. The color map of the image is transformed from RGB to HSV, and the extracted area that satisfies the following conditions corresponds to the whitened area:

$$0.055<H<0.167,\ 0.05<S<0.75,\ 0.4<V$$

Then, banalization is adapted to ensure that the extracted area has a value of 1, and the value of the other area corresponds to 0. This is followed by removing the small area to eliminate the noise area. The overall procedure is shown in Fig. 9. Fig. 10 shows a representative result of the extracted contact area in the toe area. It is observed that the extraction method worked well.

The activity of the toe area is evaluated based on the difference between the two peak contact areas in the toe area. It should be noted that the recognition of the walking phase was not needed for the evaluation, and the walking phases shown in Fig. 10 and the other figures were then manually annotated. Fig. 11 shows an example of the time-series data of the contact area in the toe area for the two groups. The first peak (in Fig. 11) occurs while pushing off prior to taking off,

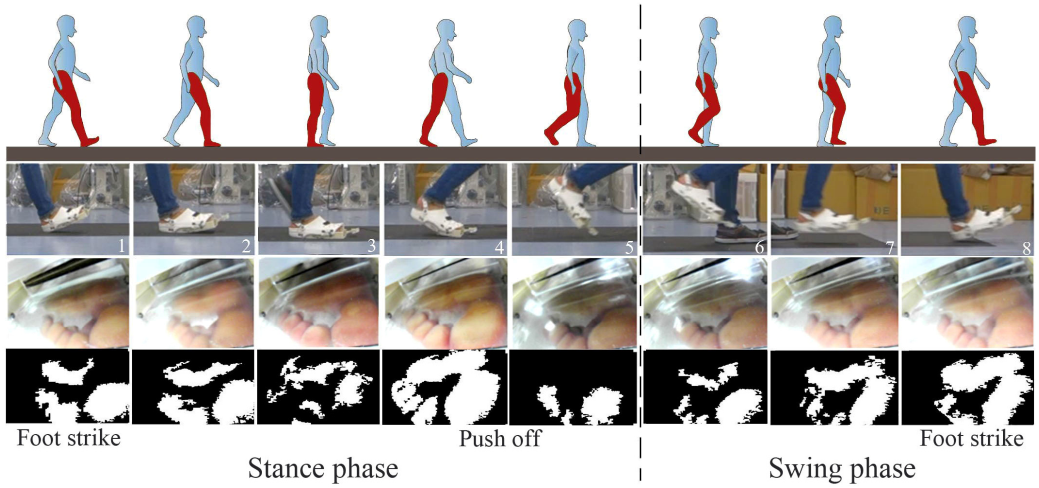


Figure 10. Representative result of the extracted contact area in the toe area

while the second peak occurs at the foot-strike phase (as shown in Fig. 10). When the results for the two groups are compared, the values of the contact areas at the second peak are similar to each other. In contrast, the value at the first peak is large for the group with no stumbling experience and small for the group with stumbling experiences. It is assumed that the former group largely moves/rotates their foot fingers for pushing off, and the value is subsequently high, and vice versa. The difference in the two peaks corresponding to the activity of the foot fingertips or toe area is then examined. This difference is termed as DPCA (Difference of two Peak Contact Areas). There are individual differences with respect to foot size and lightening. The DPCA is then normalized by the variation in the width of the contact area (Fig. 11) to compare the value for each group. The normalized DPCA (NDPCA) is given as follows:

$$\mathrm{DTCA} = \frac{A_{peak1} - A_{peak2}}{A_{peak1} - A_{min}} \quad (1)$$

where A_{peak1} denotes the contact area at the first peak, A_{peak2} denotes the contact area at the second peak, and A_{min} denotes the minimum contact area.

Algorism 1: Extraction of the contact area at the toe area	
Given	Image captured by the camera at each frame
1	Pick up the toe area from the captured image
2	A RGB image is transformed into a HSV image.
3	Extracted area satisfies $0.055<H<0.167$, $0.05<S<0.75$, $0.4<V$.
4	Banalization; Extracted area: 1, The other area: 0
5	Remove small area
6	Count the area with a value corresponding to 1
End	

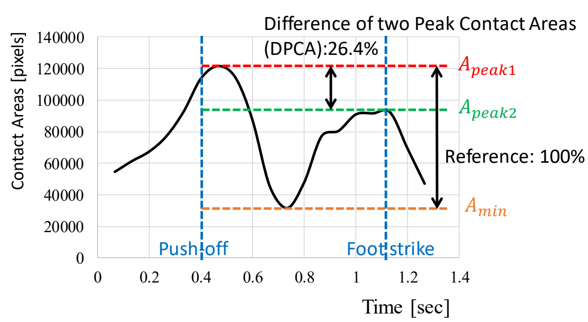
Figure 9. Procedure to derive the contact area in the toe area

D. Comparison of groups with and without stumbling experiences

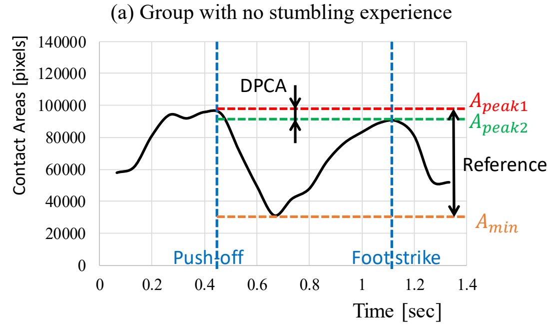
This involved comparing the results for the groups with and without stumbling experiences. As shown in Fig. 11, the DPCA is high for the group with no stumbling experience and low for the group with stumbling experiences. The normalized DPCA for each participant is evaluated, and the mean and standard deviation values are calculated for each group. The results are shown in Fig. 12. There is a statistically significant difference between the two groups. This indicates that the activity of foot fingers is high for the group with no stumbling experience and low for the group with stumbling experiences. The results validated the effectiveness of the developed clog-integrated plantar visualization system with respect to the walking evaluation for stumbling risk.

IV. Conclusion

This study presents a novel plantar sensing system. The planta is visualized and measured by a camera embedded in a clog, and the measurement can be conducted at any place and any condition. The obtained visual information is different from conventional pressure and IMU sensory data as it



(a) Group with no stumbling experience



(b) Group with stumbling experiences

Figure 11. Time-series data of the contact area in the toe area

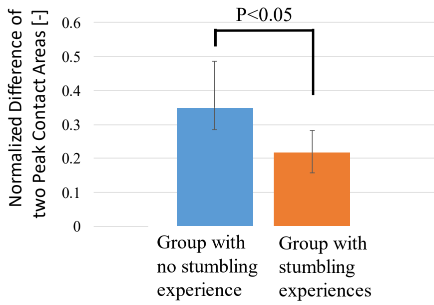


Figure 12. Mean value of the normalized Difference of two Peak Contact Areas for the groups with and without stumbling experiences

provides detailed information on the plantar surface. Thus, it is possible to accurately observe features such as the contact area, skin deformation, and skin color. Therefore, the study investigates the planta for the groups walking straight with and without stumbling experiences. The results reveal that the activity of the toe area is high for the group with no stumbling experience and low for the group with stumbling experiences. The developed sensing system provides a significant amount of information about the plantar surface. Future research will involve the investigations with more participants and with more symmetric gender distribution, the development of analysis methodologies such as automatic walking phase, and the application to health care such as fall risk assessment.

REFERENCES

[1] "Annual Report on the Aging Society," *Cabinet Office, Government of Japan*, 2016.

[2] H. Maeda, M. Shogenji, and T. Watanabe, "Evaluation of walking balance based on pose difference between normal walking and walking under multi-task conditions," *J. Robot. Mechatronics*, vol. 29, no. 2, 2017.

[3] R. L. Cromwell, R. A. Newton, and G. Forrest, "Influence of Vision on Head Stabilization Strategies in Older Adults During Walking," *Journals Gerontol. Ser. A Biol. Sci. Med. Sci.*, vol. 57, no. 7, pp. M442–M448, Jul. 2002.

[4] S. A. England and K. P. Granata, "The influence of gait speed on local dynamic stability of walking," *Gait Posture*, vol. 25, no. 2, pp. 172–178, Feb. 2007.

[5] K. Frändin, G. Grimby, D. Mellström, and A. Svanborg, "Walking habits and health-related factors in a 70-year-old population.," *Gerontology*, vol. 37, no. 5, pp. 281–8, 1991.

[6] D. Hamacher, N. B. Singh, J. H. Van Dieën, M. O. Heller, and W. R. Taylor, "Kinematic measures for assessing gait stability in elderly individuals: a systematic review.," *J. R. Soc. Interface*, vol. 8, no. 65, pp. 1682–98, Dec. 2011.

[7] J. M. Hausdorff, D. A. Rios, and H. K. Edelberg, "Gait variability and fall risk in community-living older adults: A 1-year prospective study," *Arch. Phys. Med. Rehabil.*, vol. 82, no. 8, pp. 1050–1056, 2001.

[8] S. W. Muir, K. Berg, B. Chesworth, N. Klar, and M. Speechley, "Quantifying the magnitude of risk for balance impairment on falls in community-dwelling older adults: a systematic review and meta-analysis.," *J. Clin. Epidemiol.*, vol. 63, no. 4, pp. 389–406, Apr. 2010.

[9] H. B. Menz and M. E. Morris, "Clinical determinants of plantar forces and pressures during walking in older people," *Gait Posture*, vol. 24, no. 2, pp. 229–236, Oct. 2006.

[10] W. Tao, T. Liu, R. Zheng, and H. Feng, "Gait Analysis Using Wearable Sensors," *Sensors*, vol. 12, no. 12, pp. 2255–2283, Feb. 2012.

[11] J. Rueterbories, E. G. Spaich, B. Larsen, and O. K. Andersen, "Methods for gait event detection and analysis in ambulatory systems," *Med. Eng. Phys.*, vol. 32, no. 6, pp. 545–552, Jul. 2010.

[12] N. Hegde, M. Bries, and E. Sazonov, "A Comparative Review of Footwear-Based Wearable Systems," *Electronics*, vol. 5, no. 3, p. 48, Aug. 2016.

[13] A. J. Taylor, H. B. Menz, and A.-M. Keenan, "The influence of walking speed on plantar pressure measurements using the two-step gait initiation protocol," *Foot*, vol. 14, no. 1, pp. 49–55, Mar. 2004.

[14] J. M. Burnfield, C. D. Few, O. S. Mohamed, and J. Perry, "The influence of walking speed and footwear on plantar pressures in older adults.," *Clin. Biomech*, vol. 19, no. 1, pp. 78–84, Jan. 2004.

[15] S. Preis, A. Klemms, and K. Müller, "Gait analysis by measuring ground reaction forces in children: changes to an adaptive gait pattern between the ages of one and five years," *Dev. Med. & Child Neurol.*, vol. 39, no. 4, pp. 228–233, 2008.

[16] B. Chuckpaiwong, J. A. Nunley, N. A. Mall, and R. M. Queen, "The effect of foot type on in-shoe plantar pressure during walking and running," *Gait Posture*, vol. 28, no. 3, pp. 405–411, Oct. 2008.

[17] A. J. A. Majumder, I. Zerin, M. Uddin, S. I. Ahamed, and R. O. Smith, "smartPrediction," in *Proceedings of the 2013 Research in Adaptive and Convergent Systems on - RACS '13*, 2013, pp. 434–439.

[18] J. C. Ayena, L. D. Chapwouo T., M. J.-D. Otis, and B.-A. J. Menelas, "An efficient home-based risk of falling assessment test based on Smartphone and instrumented insole," in *Proc. of IEEE Int. Symp. on Medical Measurements and Applications (MeMeA)*, 2015, pp. 416–421.

[19] H. Yu, D. Wang, C.-J. Yang, and K.-M. Lee, "A walking monitoring shoe system for simultaneous plantar-force measurement and gait-phase detection," in *Proc. of IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2010, pp. 207–212.

[20] S. Crea, M. Donati, S. M. M. De Rossi, C. M. Oddo, and N. Vitiello, "A wireless flexible sensorized insole for gait analysis.," *Sensors*, vol. 14, no. 1, pp. 1073–93, Jan. 2014.

[21] S. Yang and Q. Li, "Inertial sensor-based methods in walking speed estimation: a systematic review.," *Sensors*, vol. 12, no. 5, pp. 6102–16, May 2012.

[22] T. Hung and Y. Suh, "Inertial Sensor-Based Two Feet Motion Tracking for Gait Analysis," *Sensors*, vol. 13, no. 5, pp. 5614–5629, Apr. 2013.

[23] T. N. Do and Y. S. Suh, "Gait analysis using floor markers and inertial sensors.," *Sensors*, vol. 12, no. 2, pp. 1594–611, 2012.

[24] E. Foxlin, "Pedestrian Tracking with Shoe-Mounted Inertial Sensors," *IEEE Comput. Graph. Appl.*, vol. 25, no. 6, pp. 38–46, Nov. 2005.

[25] S. Y. Sim, H. S. Jeon, G. S. Chung, S. K. Kim, S. J. Kwon, W. K. Lee, and K. S. Park, "Fall detection algorithm for the elderly using acceleration sensors on the shoes.," in *Proc. of IEEE Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.,* 2011, pp. 4935–8.

[26] A. Rampp, J. Barth, S. Schülein, K.-G. Gaßmann, J. Klucken, and B. M. Eskofier, "Inertial sensor-based stride parameter calculation from gait sequences in geriatric patients.," *IEEE Trans. Biomed. Eng.*, vol. 62, no. 4, pp. 1089–97, Apr. 2015.

[27] B. Mariani, C. Hoskovec, S. Rochat, C. Büla, J. Penders, and K. Aminian, "3D gait assessment in young and elderly subjects using foot-worn inertial sensors," *J. Biomech.*, vol. 43, no. 15, pp. 2999–3006, Nov. 2010.

[28] H. M. Schepers, H. F. J. M. Koopman, and P. H. Veltink, "Ambulatory assessment of ankle and foot dynamics.," *IEEE Trans. Biomed. Eng.*, vol. 54, no. 5, pp. 895–902, May 2007.

[29] S. Bamberg, A. Y. Benbasat, D. M. Scarborough, D. E. Krebs, and J. A. Paradiso, "Gait Analysis Using a Shoe-Integrated Wireless Sensor System," *IEEE Trans. Inf. Technol. Biomed.*, vol. 12, no. 4, pp. 413–423, Jul. 2008.

[30] Ö. Bebek, M. A. Suster, S. Rajgopal, M. J. Fu, X. Huang, M. C. Cavusoglu, D. J. Young, M. Mehregany, A. J. van den Bogert, and C. H. Mastrangelo, "Personal Navigation via High-Resolution Gait-Corrected Inertial Measurement Units," *IEEE Trans. Instrum. Meas.*, vol. 59, no. 11, pp. 3018–3027, Nov. 2010.

[31] M. Chen, B. Huang, and Y. Xu, "Intelligent shoes for abnormal gait detection," in *Proceedings of IEEE International Conference on Robotics and Automation*, 2008, pp. 2019–2024.

[32] N. Hegde and E. S. Sazonov, "SmartStep 2.0 - A completely wireless, versatile insole monitoring system," in *Proc. of IEEE Int. Conf. on Bioinformatics and Biomedicine (BIBM)*, 2015, pp. 746–749.

[33] F. Kawsar, M. K. Hasan, R. Love, and S. I. Ahamed, "A Novel Activity Detection System Using Plantar Pressure Sensors and Smartphone," in in *Proc. of IEEE Annu. Computer Software and Applications Conf.*, 2015, pp. 44–49.