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Exploring the Assessment of Steps Using Insoles with Four-Part Pressure Sensors

[1, *] Tomoko FUNAYAMA, [2] Yasutaka UCHIDA, [3] Yoshiaki KOGURE, [4] Daisaku SOUMA and [5] Ryota KIMURA

[1] Dept. of Occupational Therapy, Teikyo University of Science, Uenohara-shi, Yamanashi, 409-0193, Japan
[2] Dept. of Life Science, Teikyo University of Science, Adachi-ku, Tokyo, 120-0045, Japan
[3] Professor Emeritus, Teikyo University of Science, Adachi-ku, 120-0045, Japan
[4] Dept. of Rehabilitation, Isogo Central Hospital, Yokohama-shi, Kanagawa, 235-0016, Japan
[5] Dept. of Rehabilitation, Seirei Yokohama Hospital, Yokohama-shi, Kanagawa, 240-8521, Japan
[1] Tel.: + 81554634411, fax: + 81554636944
E-mail: funayama@ntu.ac.jp

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Abstract: This study focused on the potential use of smart insoles incorporating four-part pressure sensors in the field of rehabilitation. The assessment of walking not only addresses walking issues but also contributes to understanding a person's health condition because the health condition manifests in the manner a person walk. With the aim of assessing the influence of activity on the body using digital devices, we investigated walking steps before and after using a walking rehabilitation robot using a wireless smart insole with four pressure sensors on each side and an accelerometer attached to the shoe. This study explored the disparities in the arrangement of pressure sensor data integrated into the insole, differences resulting from analysis methods, and their relationship with the accelerometer were investigated. The analysis results for the walking steps before robot attachment, during robot-assisted walking, and after robot attachment of distinctive features for each of the four parts of the insole demonstrate the potential of the pressure-sensor-equipped smart insole in detecting changes in walking patterns.

Keywords: Smart insole, Accelerometer, Activity assessment, Gait change detection, Rehabilitation.

1. Introduction

The manner of walking changes before and after activities, such as exercise, meals, and bathing, depending on the physical and mental conditions. Activities contribute to relaxation and fatigue, leading to changes in physical and mental conditions. The assessment of walking not only addresses walking issues but also contributes to understanding a person's health condition, because the health condition manifests in the way one walks. Walking speed is sometimes called the "sixth vital sign" and can provide insights into the body's state beyond just locomotion [1]. Wearable devices capable of measuring activities have rapidly gained attention in recent years and can also be used for rehabilitation for daily activities [2, 3]. The sensors used in these devices include acceleration, optical, temperature, and pressure sensors [4-7]. A large amount of data can be acquired using various sensors. However, the more abundant the collected data, the more complex and challenging it becomes to analyze the underlying implications. Furthermore, an increased number of sensors is often correlated with increased cost and device operation complexity. Therefore, focusing on which data are valid and how they are needed is critical for determining an individual's health condition [8, 9]. The equipment and analysis must be easy to use and understand by older people, people facing health issues, and supporting medical professionals.

In recent years, the research and development of smart insoles that record digital data to assess the effects of aging and disease for purposes such as fall prevention have progressed [10-22]. Over the years, the indications of insoles for orthopedic diseases, including osteoarthritis, diabetes, and other ailments common among older people, have been investigated in the rehabilitation and health promotion fields [23-27]. Smart insoles have the potential to assess the conditions of various illnesses and detect changes in walking patterns based on an individual's health status. Extracting crucial aspects of sensor placement and analysis contributes to practicality in rehabilitation. We have investigated the possibility of assessing how activities influence the mind and body using digital devices [7, 15, 22]. To understand the changes in health and activity, we used pressure-sensor-integrated insoles, accelerometers attached to shoes, pressure-sensor-equipped floor mats and bed mats, and wristbands incorporating optical sensors and accelerometers.

In this study, we used a robot for rehabilitation to improve walking. We examined walking before and after robot application using insoles with pressure sensors and accelerometers attached to the shoes. Additionally, considering the potential for obtaining information related to acceleration without using an accelerometer, we examined the relationship between the data from the pressure sensors on the insole and the accelerometer. We analyzed the correlation between the acceleration data and the peak values, maximum rate of decrease, and foot-ground contact time derived from the insole data at each step. The insole data were calculated for the heel, toe, inside and outside parts of the insole. Furthermore, we calculated the foot-ground contact time from the heel contact to toe-off and from one heel contact to the next and studied its relationship with acceleration data.

2. Experimental Method

2.1. Devices

We used a wireless smart insole (FEELSOLE®) that had pressure sensors. It enables measurements in four parts (the toe, heel, inside, and outside) of each foot, resulting in a total of eight parts for both feet. The insoles were calibrated before use. Calibration was performed four times: with no pressure and no feet in shoes, standing on both feet, and standing on one foot on each side. The sampling frequency was set at 50 Hz. Data were stored on the cloud using ORPHE ANALYTICS and downloaded in a CSV format.

An ORPHE CORE® accelerometer was used in this study. The data were uploaded to the cloud using the ORPHE ANALYTICS application, and the upload was confirmed by downloading the data in a CSV format. The sampling frequency was set at 200 Hz. We used two triaxial accelerometers, one for each leg, resulting a total of two devices. The assessments were conducted by attaching the devices to the outer side of each shoe, with one device on each foot. Data from both smart insoles and accelerometers were synchronized using ORPHE ANALYTICS. The robot used in this study was the Orthobot®, which is used for walking and gait rehabilitation. When attached to a long-leg brace, the robot steers its lower limbs in favorable movement patterns. The placement of the sensors is depicted in Fig. 1, and a photograph of the robot equipped for walking is shown in Fig. 2.

Fig. 1. Insole sensors and accelerometers.

Fig. 2. Walking with robot.

2.2. Measurements

We measured preusage walking, walking while wearing the robot, and postusage walking using smart insoles with built-in pressure sensors and shoes fitted with accelerometer sensors. The subject performed three walking trials of approximately 20 seconds each while wearing the walking assistance robot. The data from the third trial were analyzed. Gait analysis after use was conducted twice: once at 5 minutes and the other at 12 minutes after robot use. The 1000^{th}-6000^{th} data points were analyzed, excluding the periods immediately after the start and shortly before the end of the experiment. The subject was a man in his 60s without walking impairment who wore the robot on his right leg. This study was approved by the Human Research Ethics Committee of Teikyo University of Science.

2.3. Peak Detection

Peak values were identified from the insole data, representing the points of the highest sensor force application for the four parts (heel, toe, inside, and outside of the insole) during a single foot-ground contact. The peak values were detected using the find_peaks function from the Python library, SciPy. The threshold for peak determination was set at 50 % of the maximum value for each trial for the heel, toe, inside, and outside parts of the insole. Multiple peak values were calculated for each gait. In addition, the mean peak value and the maximum value from one heel contact to the next heel contact, that is, the maximum peak value between each step, were computed.

2.4. Determination of Decrease Rate

The rate of decrease indicates a decline in the value following the peak. In this study, it was calculated by determining the difference in the weighted averages of adjacent data points. In other words, the difference between the weighted averages of the x and x+1 data points were computed. The weighted average was obtained using five values (the target value and two values each before and after) and calculated as follows. Because of the significant influence of the central region, the percentages were calculated by assigning 40 % to the target value of the waveform, 20 % to the values before and after one target, and 10 % to the values before and after two targets. The weighted average difference can have positive or negative values; however, only negative values were used in the calculations. We calculated the mean absolute values of the negative numbers and determined the minimum value for each step.

2.5. Determination of Acceleration

Accelerometer data were examined by calculating the absolute value in each case and obtaining the square root of the sum of squares of the values along the X-, Y-, and Z-axes. The term "acceleration data" in the following refers to the square root of the sum of the squares of accelerations along three axes. The mean value for each walk and the maximum, minimum, and standard deviations of the acceleration at each step on the left and right sides were obtained.

2.6. Foot Contact Time for Each Insole Part

We calculated the ground reaction time of each sensor for the eight parts on both sides, which was the time taken for each of the eight parts to move from ground contact to lift-off. Additionally, we calculated the time from the heel contact to toe lift-off, the time from one heel contact to the next heel contact, and the time for each step, known as the step duration.

The minimum and peak values during a single walking cycle were used to calculate the ground contact time. The calculation method was as follows. The minimum value for each of the eight parts, including the left, right, heel, toe, inside, and outside, was determined. A minimum value indicates the least responsive sensor. For the peak values, we calculated the peak value at multiple ground contact times during each walking trial for the left, right, heel, toe, inside, and outside and determined the mean of the multiple peak values. To determine the ground contact and lift-off times, we added 0.2 times the difference between the mean of the peak values and the minimum value to the minimum value, setting it as the threshold.

$$thresh = Min + (Peak - Min) \times 0.2 \quad (1)$$

The initial time within the period at which values above this threshold persisted was designated as the start time, and the final time was designated as the lift-off time. The difference between the lift-off time and ground contact time was considered the ground contact time. Specifically, for each foot (left and right), we determined the first and last times above the threshold within the data between the heel start time and subsequent heel start time for each of the four parts. The values for the left heel, toe, inside, and outside were those between the start of the left heel and that of the subsequent heel. Similarly, for the right foot, the values were calculated between the right heel start time and subsequent start time. The heel start time was considered to correspond to the heel strike.

2.7. Foot Contact and Acceleration Analysis

The maximum peak value, maximum rate of decrease, foot-ground contact time, and maximum acceleration during the duration from the left and right heel contacts to the subsequent heel contacts were extracted and compared via correlations. The insole data, including the maximum peak values and the maximum rates of decrease, were collected for four parts: the heel, toe, inside, and outside of the insole. Data were separately collected for the left and right devices and for the left- and right-foot-ground contacts, resulting in four distinct patterns. The foot-ground contact duration was measured for four parts, and the measurements were conducted from the heel contact to toe-off separately for the left and right sides. The maximum acceleration was measured in four distinct patterns: left and right devices, and left and right foot-ground contacts.

For each step, the maximum peak value, maximum rate of decrease, foot-ground contact time, and maximum acceleration were calculated. Data for steps were obtained for four trials: before robot attachment, during attachment, 5 minutes after attachment, and 12 minutes after attachment. A comparison between the left and right feet was conducted for the right-foot-ground contact after the left foot made contact, and the right-foot-ground contact immediately before the left foot made contact. In other words, the comparison focused on the right-foot-ground contact in two steps: one occurring after the ground contact of the left foot, and the other shortly before the ground contact of the left foot. We examined the relationship by investigating the correlations between the maximum acceleration, maximum peak value, maximum decrease rate, and the duration of foot-ground contact and calculated Pearson's correlation coefficient. Pairs with high correlation were extracted, and an analysis was conducted on whether the data from the insole and the data from the accelerometer were from the same-side foot or the opposite-side foot. Furthermore, we made a distinction between data from the same step durations and data from opposite step durations (for example, acceleration during the right step and insole during the left step; see Fig. 3). The analysis also included an examination of the location of the insole.

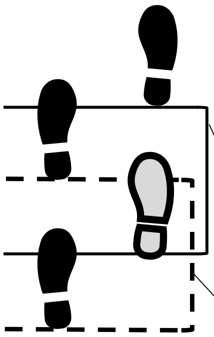

Fig. 3. Two periods in three steps.

3. Results

3.1. Peak Values of Insoles

The mean peak values for 5 and 12 minutes after robot usage were compared with the values before robot usage. The value before robot usage was considered 1, and the rates of change were calculated. The values are listed in Table 1.

Table 1. Rate of change in peak values.

Part	Before	During	5 min after	12 min after
L_heel	1.00	1.12	1.01	1.04
L_toe	1.00	0.97	1.03	1.03
L_inside	1.00	1.11	1.13	1.09
L_outside	1.00	0.84	0.86	0.96
R_heel	1.00	0.91	1.05	1.20
R_toe	1.00	0.44	0.96	0.93
R_inside	1.00	0.93	1.09	1.12
R_outside	1.00	0.48	0.90	0.83

In terms of the peak values, the values decreased in some areas, but overall, the peak values increased. From the data for 12 minutes after robot detachment, on the side where the robot was attached, the right side showed a decrease on the outside and an increase on the inside. The toe part showed a decrease, whereas the heel part showed an increase. During robot attachment, the attached side showed a decrease. The peaks decreased, indicating a decrease in momentum.

3.2. Rate of Decrease

The difference in the weighted mean difference, that is, the difference in the rate of decrease, at each walking session was calculated using the pre-robot as the reference. The mean values for each walk were compared (see Table 2).

Table 2. Rate of change in decrease.

Part	Before	During	5 min after	12 min after
L_heel	1.00	1.09	1.05	1.04
L_toe	1.00	1.03	1.39	1.50
L_inside	1.00	1.33	1.60	1.53
L_outside	1.00	0.74	0.98	1.38
R_heel	1.00	1.14	1.19	1.56
R_toe	1.00	0.34	0.94	0.96
R_inside	1.00	0.84	1.18	1.30
R_outside	1.00	0.45	0.79	0.79

In terms of the weighted mean difference, that is, the decrease rate, the values decreased in some areas, but overall, the values increased. Based on the data for 12 minutes after robot detachment, on the side where the robot was attached, the right side showed a decrease on the outside and an increase on the inside. The toe part showed a slight decrease, whereas the heel part showed an increase. During robot attachment, the attached side showed a decrease. The changes were minimal, indicating a slow and gradual transformation.

3.3. Acceleration

For acceleration, in addition to the mean value, we calculated the minimum value, maximum value, and standard deviation to assess the magnitude of the movement variability. Table 3 lists the ratios during and after robot usage, with the pre-robot condition as the baseline for each statistical parameter.

The minimum values of acceleration on the left and right sides decreased, but the other values increased for the measurements conducted 5 minutes after detachment. The left maximum value at 12 minutes slightly decreased. The standard deviation increased by more than 40 % on both the left and right sides at 5 and 12 minutes after detachment. During the robot attachment, the right-side maximum and left-side minimum values increased, whereas the others decreased.

Table 3. Rate of change in acceleration.

Part	Before	During	5 min after	12 min after
L_mean	1.00	0.96	1.12	1.08
R_mean	1.00	0.89	1.13	1.10
L_max	1.00	0.85	1.28	0.96
R_max	1.00	1.45	1.75	1.10
L_min	1.00	1.63	0.95	0.83
R_min	1.00	0.80	0.72	0.44
L_std	1.00	0.97	1.45	1.43
R_std	1.00	0.83	1.53	1.41

3.4. Foot Contact Time for Each Part

In addition to the four regions of the insole, we calculated the time from the heel to the toe and from one heel to the next heel, representing the time for one step. The results for the left and right insoles are presented in Fig. 4 and 5, respectively. The unit is in seconds. The figure illustrates the mean values for six items in each walking condition: before robot attachment, during attachment, 5 minutes following detachment, and 12 minutes following detachment. The bars in the figure are blue for the heel, red for the toe, gray for the inside, yellow for the outside, bright green for heel to the toe and dark green for one step.

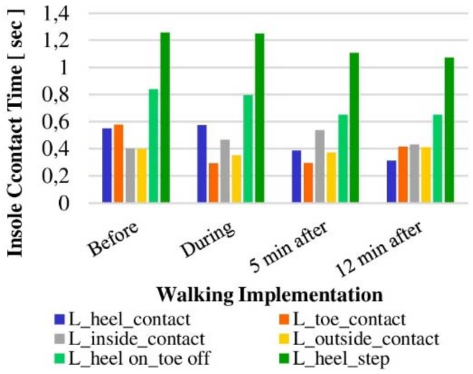

Fig. 4. Left-foot-ground contact time.

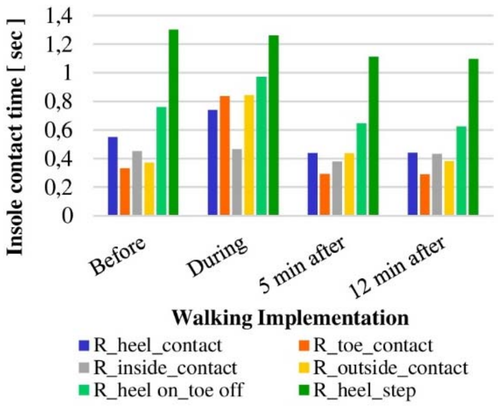

Fig. 5. Right-foot-ground contact time.

During the robot use, the time spent on the left toe decreased, whereas the time spent on the right toe increased. After the robot was used, an overall tendency of decrease in time was observed. Table 4 lists the percentage changes relative to the pre-robot conditions.

While walking with the robot attachment, the right foot, which was attached to the robot, experienced increased durations of heel, toe, inside, outside, and heel ground contact to toe release.

Table 4. Rate of change in foot contact time.

Part	Before	During	5 min after	12 min after
L_heel	1.00	1.05	0.71	0.57
L_toe	1.00	0.51	0.51	0.72
L_inside	1.00	1.16	1.33	1.08
L_outside	1.00	0.88	0.94	1.03
L_heel on -toe off	1.00	0.95	0.77	0.77
L_heel_step	1.00	0.99	0.88	0.85
R_heel	1.00	1.35	0.80	0.80
R_toe	1.00	2.52	0.88	0.88
R_inside	1.00	1.03	0.84	0.96
R_outside	1.00	2.27	1.18	1.03
R_heel on -toe off	1.00	1.28	0.85	0.82
R_heel_step	1.00	0.97	0.86	0.84

Within the plantar ground contact time of the left foot without the robot, the left foot without the robot was more than 20 % shorter at the toe and less than 20 % shorter at the heel contact to toe-off and heel contact to next heel contact. In contrast, the heel and inside were longer. For both the left and right sides, the time from heel contact to the next contact decreased. The duration of the left-heel contact without the robot increased, and the duration of the toe contact decreased. In addition, the duration for the outside of the insole decreased, whereas that for the inside increased. While walking with the robot attachment, the length of time spent by the left leg, which was not attached to the robot, shifted from the toe to the heel and from outside to inside.

Five minutes after the robot was removed, the pace of walk became significantly fast, with durations more than 20 % shorter on the left heel, toes, and from the heel ground to toe-off, and 10 % shorter overall on the other parts. The two parts that were longer were the left inside and the right outside. On the left side without the robot, an increase in the loading time shifting from the outside to the inside was observed. whereas, with the robot attached to the right, an increase was observed for the loading time shifting from the inside to the outside.

Even after 12 minutes of robot-assisted walking, a trend similar to that after 5 minutes was observed. In comparison before the robot was attached, the difference in the trend after 5 and 12 minutes was that the left outer sides were longer than before the robot attachment. Compared to the case before robot attachment, the changes only after 5 and 12 minutes showed that on the left side, the inside was shorter, and the outside was longer, and on the right side, the inside was longer, and the right outside was shorter.

An exceptional ground reaction, presumed to be associated with U-turns and different from typical steps, was observed. Five minutes after the robot was removed, a step was observed in which two inside peaks appeared between the left heel peak and the subsequent peak. The raw data from the sensors are shown in Fig. 6. The calculation of foot-ground contact time was based on the left heel contact; therefore, in this step, the extracted foot-ground contact times for both the inside and outside increased. A graph of the foot-ground contact times was plotted (Fig. 7). Despite being an exceptional step, it has not been excluded and is included in the calculations of the foot-ground contact time.

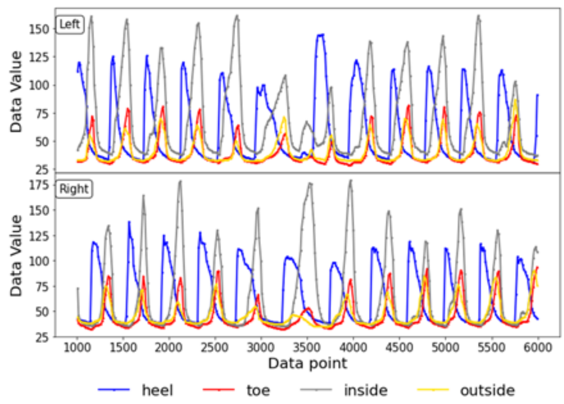

Fig. 6. Raw data for 5 min after robot detachment.

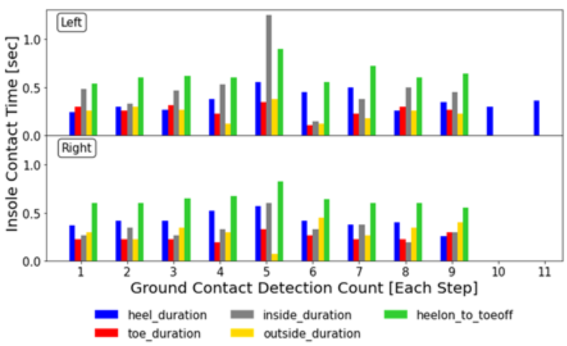

Fig. 7. Foot-ground contact time per step 5 min after robot detachment.

While U-turns were performed in each walking session, such exceptional steps were observed only walking when 5 minutes after removing the robot. In calculating the foot-ground contact time, a step in which only the heel was extracted was also observed in other trials. The calculation method for extracting foot-ground contact time used in this study is considered to be more suitable for utilizing heel data compared to the other three parts.

3.5. Foot-ground Contact and Acceleration

The number of steps in each walking trial, combined for the left and right sides, was 17 before robot attachment, 17 during attachment, 20 at 5 minutes after removal, and 20 at 12 minutes after removal. A total of 74 steps were taken. We examined the relationship by investigating the correlations between the maximum acceleration, maximum peak value, maximum decrease rate, and the duration of foot-ground contact. Pearson's correlation coefficient was used for the calculations.

The results of the correlation analysis revealed no items with a correlation coefficient of 0.6 or higher. Items with a coefficient of 0.4 or higher included 25 pairs in the relationship between the right step with the attached robot and the preceding left step in terms of time. There are 24 pairs in the relationship between the right step with the attached robot and the subsequent left step. Of the 49 pairs with relatively high correlation, 17 were pairs in which the accelerometer and insole were on the same side of the foot, and 32 were pairs in which they were on opposite sides (Table 5). The correlation tended to increase when the accelerometer and insole were placed on different sides of the foot. In addition, we checked the time period from which 32 pairs were extracted in which the acceleration and insole were on opposite sides and found 14 data pairs for the same time period and 18 data pairs for different time periods, that is, at different left and right step times. Through a detailed study of the acceleration at different time periods for 18 pairs, the acceleration data pairs during the step time of the same foot on the side for which the data were acquired were 12, and the acceleration data pairs during the step time of the other foot for which the data were not acquired were 6.

Table 5. Acceleration-Insole high correlation.

Acceleration Insole	Highly Correlated Numbers	Same Time Period	Different Time Period
Same side	17	8	9
Opposite	32	14	**18**

Among the 12 pairs with a high correlation between the acceleration and insole during the step period, the insole data comprised five from the toe, four from the outside, two from the inside, and one from the heel. This suggests that the insoles with a high correlation with acceleration are on the opposite side of the foot where the accelerometer is attached and are not in the same step period. Moreover, the areas of the insole with a correlation to acceleration are inclined towards the toe and slightly to the outside.

4. Discussion

The smart insole detected variations in the peak values, rates of decrease, and durations of foot-ground contact before and after robot use. Among the four parts, the right outside, where the robot was worn, exhibited a tendency to present different results compared to the other three. In addition, changes were observed on the inside right, which might be correlated with the outside.

Five minutes after detaching the robot, based on the foot-sole ground contact time on the left side without the robot, the load time increased as it moved from the outside to the inside. However, on the right side with the robot, the load time increased as it moved from the inside to the outside. From the peak values and decrease rates after detaching the robot, the right outside showed a decrease, whereas the inside showed an increase. This suggests a potential change in the distribution of weight-bearing along the left-right axis. The following considerations are possible. On the inside of the right side, a possibility of rapid and forceful ground contact was observed during rapid movements, potentially increasing the peak values and decrease rates. Whereas, the outside experienced a decreased load, resulting in a reduction in the peak values and decrease rates, leading to a gradual change. Regarding the acceleration on the left side, all values on the left side increased based on the decrease-rate data, suggesting that the movements were accelerating.

Based on the foot-ground contact time, it was observed that the time for one step was shortened on both the left and right sides. Although a slight increase occurred on the right outside and left inside, the overall trend indicated a reduction. Upon reviewing the steps during U-turns through video observations, a walking pattern was identified in which 5 minutes after robot detachment, rotation occurred around the right foot as an axis. Analyzing the steps that deviate from the norm separately from regular steps simplifies the observation of the characteristics during normal steps. However, distinctive features may also appear during exceptional steps. It is crucial to focus on analyzing exceptional steps while concurrently examining regular steps and recognizing the significance of both aspects. In addition, the extraction of step times was most reliably detected when focusing on the heel.

In terms of the acceleration and time, it is apparent from the foot-ground contact time that the duration of a single step on the left and right sides decreased. From the acceleration data, it was observed that the acceleration decreased during landing; however, after takeoff, an overall increase in acceleration was observed, and the minimum values decreased. Considering the increased standard deviation and shift towards increased maximum values and decreased minimum values, it is possible that the movements became more dynamic. No consistent correlation was observed with acceleration. However, it is possible that data from the pressure sensor insole on the opposite side of the evaluated foot were related. In addition, a focus on the toes is suggested. The toe is a region with weaker data output and a lower load compared with other parts. It is believed that detecting changes in walking patterns can be facilitated by implementing sensitive sensors, finely tuning their positions, and employing sensor innovations in this less-loaded region.

5. Conclusions

Distinct characteristics were observed in the heel, toe, and inside and outside regions of the insole. Incorporating sensors into insoles based on captured features for consideration of sensitivity and position is important for walking assessment. In the future, we plan to expand the dataset and investigate analysis methods to further analyze the relationship between acceleration and pressure sensors.

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