Master's Thesis
석사 학위논문

The Long-term Gait Speed Monitoring System Using a Single IMU for a Daily Life Use

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Advisor : Professor 김종현

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by

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Robotics Engineering. The study was conducted in accordance with Code of Research Ethics[1]

1. 2. 2015.

Approved by

Professor 김 종 현 (Signature)
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(Co-Advisor)

[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

The Long-term Gait Speed Monitoring System Using a Single IMU for a Daily Life Use

Minsu Song

Accepted in partial fulfillment of the requirements for the degree of
Master of Science.

12. 4. 2014.

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ABSTRACT

The gait speed estimation by using inertial measurement unit (IMU) is an efficient method for use of daily life. By attaching one IMU on heel side of the foot, we can easily estimate the user's walking speed. In order to adapt the estimation to daily life, we have considered long-term gait speed estimation based on a single IMU. Of various types of walking pattern that can be appeared during the long-term daily life walking, this study mainly focuses on the straight line walking because the walking pattern has been widely used to assess the gait function. For accurate estimation of the user's walking speed, we need to perform a gait cycle segmentation in order to reduce the drift error that comes from double integration of acceleration data of IMU. In this study, the gait cycle is segmented by a firm event, foot-flat. In order to verify the foot-flat detection by using IMU, one subject wore both an IMU and force sensing resistors, and walked on a treadmill. After that four healthy subjects (2M 2F) participated on verifying the gait speed estimation and incline estimation on the treadmill. Finally, four healthy adult subjects (2M 2F) participated on long term gait speed estimation experiment, to verify the excluding algorithm which can exclude various walking patterns such as stair ascent and descent, ramp ascent and descent from long term gait. By extracting the straight line walking on horizontal surface from the long term gait, we can simply acquire the preferred walking speed of the user. The gait speed estimations of the treadmill walking and long term straight line walking were successful. Further studies are needed for accurate estimation and categorization of various gait patterns for the future clinical use.

Keywords: Single IMU, Long-term gait, preferred gait speed, daily life, gait pattern recognition.

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I. Introduction

1.1 Background

Emerge of aging society has brought academic interest on enhance of life quality for elderly people. Elders in nursing home are increasing and the assistance for clinicians are required. To maintain the health of elder and improve their quality of life, assessing health status of elderly people is crucial. But most of the assessment procedures takes a lot of time and effort. Gait speed is the key assessment tool for lower limb disorders and other relative abnormalities. Gait speed can be an assessment tool for severity of Parkinson's disease, stroke, or cerebral palsy, and it can also perform as an assessment tool for elder people. The gait speed measurement can perform as a predictor which can identify mortality of elder adults [1], and incident dementia of elder adults [2]. These are the reason of clinicians and physical therapists perform certain assessments in order to check the gait speed of individuals [3, 4].

There are several methods to assess walking speed, such as 10 meter walk test (10MWT) [5], and 6 minute walk test (6MWT) [6]. 10MWT is the test for individual walking 10meters without assistance. There are two types of 10MWT. The individual walks without assistance 10 meters, and the time is measured for the intermediate 6 meters. In other way, individual walks without assistance 14 meters, in order to accelerate 2 meters to preferred speed and after 10 meter of measuring time, 2 meters to decelerate. 6MWT is the test that individual walks 3minute at corridor, in their preferred speed.

There are problems of these tests. 6MWT and 10MWT requires large spaces such as long corridor, which is difficult to find in busy hospitals or other medical facilities. These methods are also time consuming, and requires extra manpower for measurement. For additional, because of the existence of observer, patients/individuals can be anxious or nervous and make an effort to enhance their gait pattern better. By the extra effort caused by anxiety, the individuals would not show their own natural preferred gait patterns during the test. To overcome these problems, we propose the single inertial measurement unit (IMU) based long-term gait speed estimation system. By adapting this system, individuals can freely walk in their daily-life without any kind of anxiety, in order to show their natural preferred gait. And also this system can be performed outside of the hospital facility, without any kind of gait lab or corridors which might occupy large spaces in medical facilities.

1.2 Gait measurement using IMU

There are many types of gait parameter measuring systems using IMU. One group used single IMU attached on pelvis to check the individual's bilateral step length [7]. It double integrates the IMU acceleration component in the direction of progression between the instants of two consecutive heel strikes, in order to estimate the stride length. But the detection of heel strike is not performed from actual distal limb, and it is based on pelvic movement to estimate lower limb kinematics. The stride length is estimated by calculation using estimated angle of lower limb rotation and measured length of leg. So even if it is able to estimate the stride length, the accuracy may not be guaranteed for long-term clinical use.

The other group used four IMUs on lower limb in order to check the spatial and temporal parameters of gait [8]. Later, they challenged to reduce the number of the sensors into two IMUs on each shank [9]. The IMUs detect terminal contact (Toe-off) and initial contact (Heel-strike) to perform gait cycle segmentation by using gyroscope on each shanks. Only gyroscope for one lateral axis is used to estimate joint angles and displacements, and other parameters. By preferring gyroscope and using gyroscope only, multiple IMUs were required. In these days, IMUs contain both gyroscope and accelerometer, so selecting either of them are unnecessary. And by using both gyroscope and accelerometer in same time, decrease of the number of IMU was available.

Using multiple IMUs are difficult for user to attach by themselves, which make the system inappropriate for long-term daily use. To use IMU as daily life monitoring device, the single module which is easy to attach is required. And the accuracy of gait speed estimation should be acceptable as good as other systems. There is a system which uses single IMU attached on one shank [10, 11]. The method is to assume leg as an inverted pendulum model on 2-D surface (x-y axis). IMU is attached on shank and the system detects shank-vertical, the posture which the shank is vertical to the ground surface and the angular velocity of gyroscope is zero. The detected moment of shank-vertical is used as start and end point of gait cycle. But the problem was the shank-vertical they detected doesn't show actual zero angular velocity because of the alignment issues of IMU. The misalignment of the IMU can cause errors through 2-D surface analysis which the system assume, and these errors lead to inaccurate gait speed estimation. Also, the method is vulnerable in analyzing the toe-out gait, the gait pattern which the toe is spread outward during the walking. The analysis of the toe-out gait have to consider z-axis movement in 3-D space.

The most of the methods possess the lack of consideration for long-term daily life monitoring. Some methods use multiple IMU, which is difficult to attach in daily life use. Some methods need to measure the length of body segments in order to estimate the kinematics of distal limbs, which can be easily changed through occasions because of the clothing or measurement errors. The single IMU attached on shank [10, 11] used inverted pendulum model for speed estimation, but its segmentation is not reliable and the method assume subjects are walking in 2-D plane behavior, which doesn't consider z-axis movement in 3-D space. Our model which use single IMU using both gyroscope and accelerometer, is represented on Figure 1.

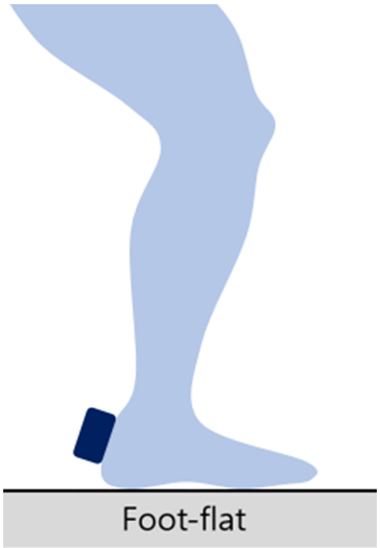


Figure 1. Single IMU on heel side of the foot for gait speed estimation

The foot has firm event during gait cycle called the foot-flat [14], which entire foot is horizontally attached to the ground surface. The foot-flat happens between heel strike and toe off, and it can become a solid beacon for gait cycle segmentation, because the foot instantly stops during the foot-flat phase. To detect the foot-flat, we attach IMU on foot in order to estimate gait speed. Furthermore, we can simply categorize if the walker is performing normal walk, inclined walk, or stair walk by using the foot mounted IMU. Also, the system can provide compensation of sensor tilt and speed estimation of the toe-out gait, the major problem of foot-mounted IMU gait analysis system by including the z-axis acceleration to analyze the gait in 3-D space. In our proposing method, we use single IMU on the heel side of the foot described in Figure 1. We use accelerometer to detect foot-flat in order to perform gait cycle segmentation, in order to estimate the walking speed, and to detect the inclination of the surface. We avoid using magnetometer, which can be affected by possible magnetic obstacles outside the controlled laboratory.

1.3 Long term gait speed monitoring

The inertial measurement unit is efficient device to achieve the concept of long term gait speed monitoring, which is the final goal application of gait speed estimation system. The gait speed estimation can replace the gait speed measuring methods such as 6MWT and 10 MWT. But still, this is not actual out of lab measuring. The key idea is that user attach inertial measurement unit by themselves in their daily life. The system enable the clinicians to regularly monitor the change of the preferred gait speed of the patient. To make this possible, we need to extract the preferred gait speed from the various gait patterns of the daily life walking.

The goal of gait speed measurement methods such as 6MWT and 10MWT are to determine the subject's walking speed on straight corridor, which can be expressed as straight line walking. Therefore, the targeted gait parameter of the system is preferred gait speed of the user which occurred during the straight line walking on horizontal surface. But daily life contains walking on ramps, stairs, and other environment. Our goal is to exclude these various gait patterns except the straight line walking on horizontal surface. There are studies using IMU to define patterns of non-straight gait such as turning [12], stair ascending and descending [13]. We suggest foot mounted IMU based gait pattern recognition algorithm using inclination angle of the foot during the foot-flat phase, and inclination angle calculated by displacement during one stride. The algorithm is able to define non-straight gait patterns on long-term data in order to exclude them. Our goal is to find user's preferred walking speed on straight line walking in daily life, and to detect other types of gait patterns for excluding.

1.4 Goal of the study

This study is focused on developing the gait speed estimation system for long term gait speed monitoring. The study includes; verifying accelerometer-based gait cycle segmentation method for gait speed estimation, and developing the algorithm which can reduce errors and exclude various walking behaviors except the straight line walking on horizontal surface for accurate and selective long term gait speed estimation.

II. Method

2.1 Device

We use single IMU on heel side of the one distal limb; the foot. The IMU (Shimmer 2r, Fig. 2) have 9 degree of freedom (DOF) inertial measurement sensors (3DOF accelerometer, 3DOF gyroscope, 3DOF magnetometer). Our method is based on 3DOF accelerometer and 3DOF gyroscope for total 6DOF data analysis. Shimmer 2r has battery power for 8 hours of Bluetooth based online data streaming time, and more than 18 hours of offline data logging to 2GB micro SD card. Shimmer 2r is proper device for long-term analysis. Sampling rate is 204.8 Hz for all trials, and second order Butterworth low pass filter with 4Hz of cutoff frequency was used to minimize the error.

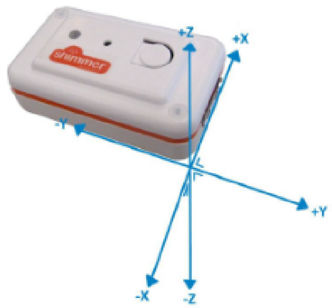


Figure 2. Shimmer 2r IMU.

The four channel force sensing resistor (Delsys Trigno FSR) was used to perform an experiment to compare and verify foot-flat detecting method using IMU with actual foot-flat detected by FSRs attached below the foot.

We use Woodway PPS55 medical treadmill which can provide speed 0-20km/h, and 0-25% of inclination.

2.2 Gait cycle segmentation

Accurate gait cycle segmentation is the key factor for an accurate gait speed estimation. Entire process of gait speed estimation can be divided into three phases, gait cycle segmentation, elimination of offsets and errors, and finally, speed estimation. In gait cycle segmentation, we divide collected data into each cycle of stride to analyze, and reduce the effect of drift error. The need of gait cycle segmentation for the gait speed estimation using IMU is well known [10]. The algorithm detects foot-flat, when both heel and toe are attached to the ground. We assume that the foot-flat phase contains instant stop of the foot, which we can notice by accelerometer. When the IMU is in constant or zero velocity, the only acceleration affects IMU is the gravitational acceleration. By synthesized value of every acceleration magnitudes, we can calculate the total amount of acceleration occurred on the foot. When the foot is on zero-velocity, the gravitational acceleration can be calculated as equation (1).

$$g_{calculation} = \sqrt{(a_t)^2 + (a_n)^2 + (a_z)^2} \tag{1}$$

The gravitational acceleration gives us information about the axis transformation. Figure 3 shows the local axis of the IMU and global axis. The axis t and n is tangential and normal axis of attached IMU, and axis z is positive outward of the paper. We need to rotate the local n-t-z axis to x-y-z global axis. We assume z axis is horizontal to the ground surface.

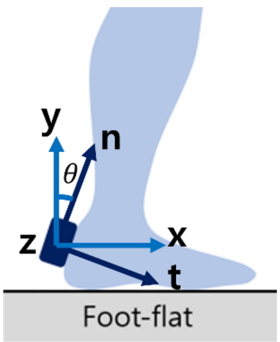


Figure 3. Local and global axis of IMU

To calculate the rotated angular position of local axis from global axis, we need to measure the accelerations on each t-n-z axis during stop position. The only factor affects IMU during stop position is the gravitational acceleration. To measure the initial position of the local axis, and calculate the accelerations of the t-n-z axis, the user is asked to stand still for few seconds on the horizontal surface, right after the IMU starts recording. This few seconds of standing is called the initializing phase. During the initializing phase, we calculate acceleration on the IMU and its gravitational axis. Equation (2) represents the mean accelerations of each local axis for initial position.

$$\begin{cases} a_{t,n,z-init} = \frac{\sum_{i=1}^{n} a_{t,n,z-i}}{n} \\ n = number\ of\ initializing\ data \end{cases} \tag{2}$$

By calculating the arctangent of initial accelerations in stop phase, we can find the rotated angle of local axis. The angle of rotated angles are calculated as equation (3)

$$\alpha = \mathrm{atan}\left(\frac{a_t}{a_n}\right),\ \beta = \mathrm{atan}\left(\frac{a_a}{a_t}\right),\ \gamma = 0 \tag{3}$$

The angle α is the angle of pitch, rotation of Z axis. The angle β is the angle of Yaw, rotation of Y axis. We attached z axis to be horizontal to ground surface, as the angle γ is zero.

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \mathrm{R} \begin{bmatrix} a_t \\ a_n \\ a_a \end{bmatrix},\ R = \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma \\ -s\beta & c\beta s\gamma & c\beta c\gamma \end{bmatrix} \tag{4}$$

We use 3x3 Z-Y-X Euler angles. The rotated acceleration $a_{x,y,z}$ can be represented as equation (4). R is the rotational matrix for Z-Y-X Euler angles. As the transformation is finished, we obtain zero offsets due to gravity on x and z axis, and offset of $g_{calculation}$ on y axis as shown in Figure 4. The black line represents raw n-t-z accelerations, and the blue dot line represents rotated x-y-z accelerations.

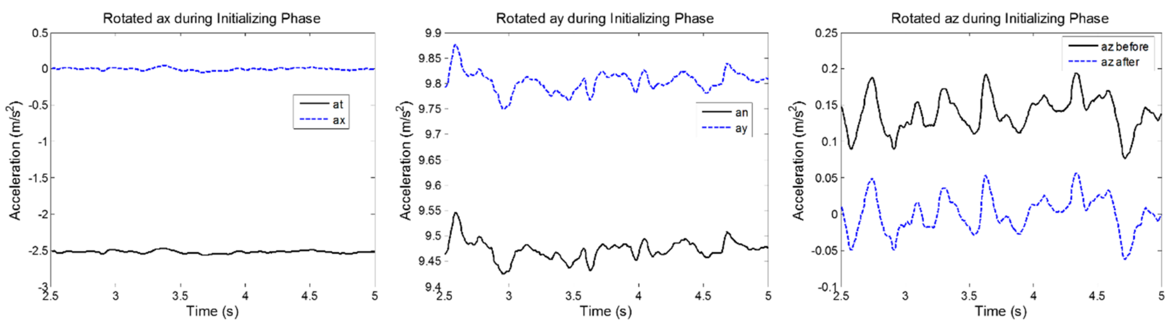


Figure 4. Rotated accelerations for x, y, and z axis.

Because of the sensor noises and imperfect calibrations, there is a small amount of offset of accelerations even in zero-velocity. We find the largest noise during the initialization phase and use it as a threshold of detecting the foot-flat, in order to perform gait segmentation as equation (5). The term g_{init} is the calculated gravitational acceleration. The term noise is the maximum noise of the gravitational acceleration during the initialization phase. The foot-flat is a phase that foot is horizontally still during the stance phase of gait, between heel strike and toe off [14]. The stance phase is occurred after mid swing, so we detect the foot-flat whenever after angular velocity ω_z has exceeded 100deg/sec. The detecting condition of foot-flat is explained in equation (6).

$$g_{threshold} = \begin{cases} g_{min} = g_{init} - noise \\ g_{min} = g_{init} + noise \end{cases} \tag{5}$$

$$After\ \omega_z > 100\ deg/sec, \qquad \begin{cases} g_{init} - g_{cal} < 0.01\ (minimum\ threshold) \\ g_{cal} > g_{min} \\ g_{cal} < g_{max} \\ \omega_z < 10\ deg/\sec\ \ (minimum\ threshold) \end{cases} \tag{6}$$

After the mid swing is occurred, we find the point that synthesized acceleration error is lower than 0.01, which is between threshold, and angular velocity of z axis is low enough to assume it stopped. This point is when the foot is stopped and in the case of straight line walking, the foot-flat is occurred. Figure 5. Shows the detected point of foot-flat using conditions of equation (6). We use the stride between two foot-flat in order to estimate gait speed and stride length.

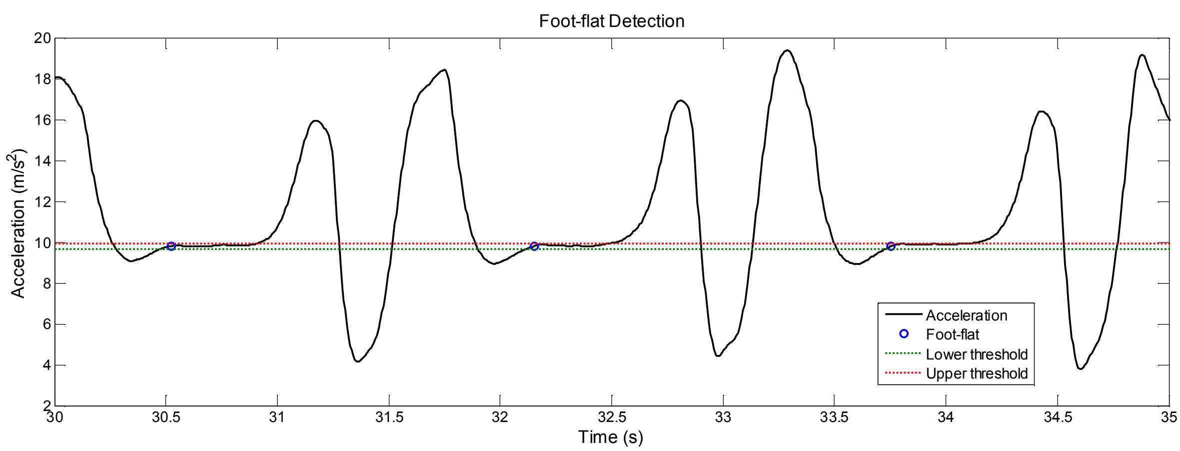


Figure 5. Result of foot-flat detection

2.3 Gait speed estimation

The gait speed estimation is performed for each stride. First, we calculate the initial angular position $\theta_{initial}$ of IMU using means acceleration during initializing phase $a_{x,init}$ and acceleration $a_{y,init}$ using equation (7).

$$\theta_{initial} = \text{atan}\left(\frac{a_{x,init}}{a_{y,init}}\right) \tag{7}$$

The angular position $\theta_{foot-flat}$ can be obtained using arctangent of the acceleration on axis x and y during the foot-flat. The angular position $\theta_{foot-flat}$ is subtracted from the angular position θ_{init} in order to calculate the inclination of the surface which foot-flat is occurred.

$$\theta_{inclination} = \theta_{init} - \theta_{foot-flat} \tag{8}$$

We use the angular position $\theta_{foot-flat}$ as the start position for calculating the angular change during the stride. The angular change θ can be obtained as following equation. The term T is time spent during one stride, foot-flat to foot-flat.

$$\theta(t) = \int_0^T \omega_z(t)dt + \theta_{foot-flat} \tag{9}$$

If we don't reset the start position of IMU angle using the accelerometer based angular position $\theta_{foot-flat}$, the integration of angular velocity ω_z will be massively contaminated by drift error of gyroscope. But if we don't use gyroscope based integration, we cannot calculate the orientation of IMU during swing phase. Figure 6 shows the angular position change during gait. The red circle is the example of drift correction, resetting the angular position of IMU using accelerometer.

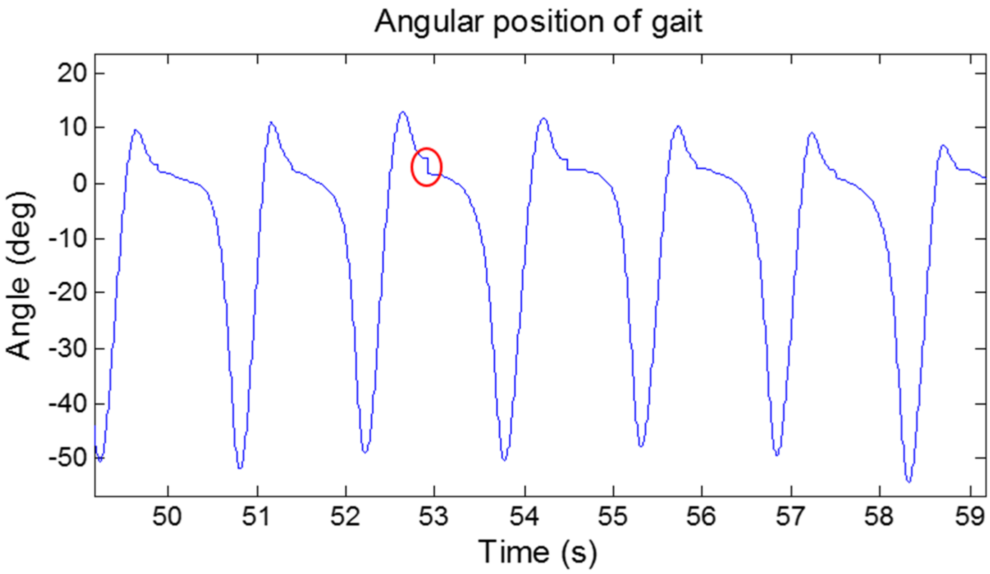


Figure 6. Angular position during gait

The angular position of IMU is used to calculate the acceleration orientation on the view point of global axis x-y-z. We calculate the rotated $a_{x,y}$ to obtain the orient-changing acceleration $a_{x2,y2}$, due to swing of leg.

$$\begin{bmatrix} a_{x2} \\ a_{y2} \end{bmatrix} = \begin{bmatrix} cos\theta(t) & -sin\theta(t) \\ sin\theta(t) & cos\theta(t) \end{bmatrix} \begin{bmatrix} a_x(t) \\ a_y(t) \end{bmatrix} - \begin{bmatrix} 0 \\ g \end{bmatrix} \tag{10}$$

By integrating the obtained orient-changing acceleration $a_{x2,y2}$, we can calculate the velocity of one stride for each axis.

$$v_{x,y,z}(t) = \int_0^T a_{x2,y2,z}(t)dt + v_{x2,y2,z}(0) \tag{11}$$

We double integrate acceleration to calculate the displacement for each axis. By integrating velocity of one stride for each axis, we can obtain the displacement of one stride for each axis. But double integration also contains drift error because of integrating small errors and offsets. We expect the velocity on each foot-flat should be close to zero, as the foot-flat means zero-velocity state. But there are drift error as shown in Fig. 7. That is why we assume this velocity error as offset and subtract triangle of displacement error from calculated displacement. The equation (12) shows the error reducing by subtracting the triangle-shape displacement error calculated by multiplying the 0.5 with final velocity of end point and stride time T.

$$s_{x,y,z}(t) = \int_0^T v_{x,y,z}(t)dt - \frac{1}{2}v_{x,y,z}(T) \cdot T \tag{12}$$

The final process to obtain the estimated stride velocity due to direction of gait is to synthesize the each displacement vectors. Generally, we can easily synthesize the vectors using equation (13).

$$s_d = \sqrt{s_x{}^2 + s_y{}^2 + s_z{}^2} \tag{13}$$

But there are some specific situations where we cannot obtain the displacement due to direction of gait by equation (13). When the subject is walking in toe-out pattern of gait, and if the subject lost balance and show the swaying stride, synthesis of vectors will be extremely increased than usual gait pattern because of the undesired lateral step. The Figure 7 shows the example of this situation.

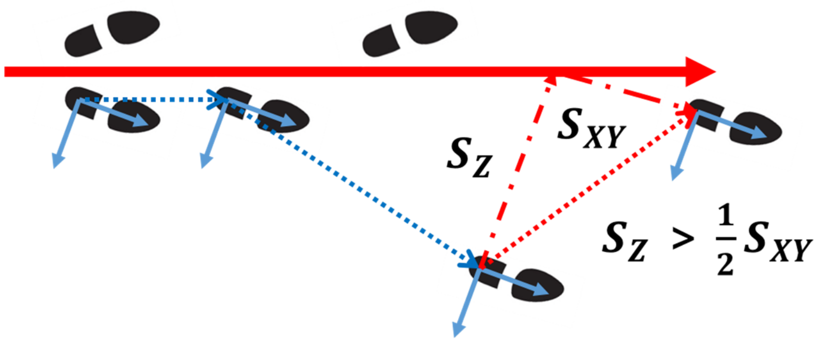


Figure 7. Sway pattern of toe-out walker

The red thick arrow of Figure 7 represents the desired direction of gait. And the toe-out walker has shown lateral swaying walking pattern. During this swaying, the displacement of S_z exceeds the 50% displacement of x-y plane, S_{xy}. In this particular situation, we want to exclude the lateral displacement due to sway, and only consider the displacement of the desired direction of gait. We use simple geometrically analyzed synthesis method shown in Figure 8.

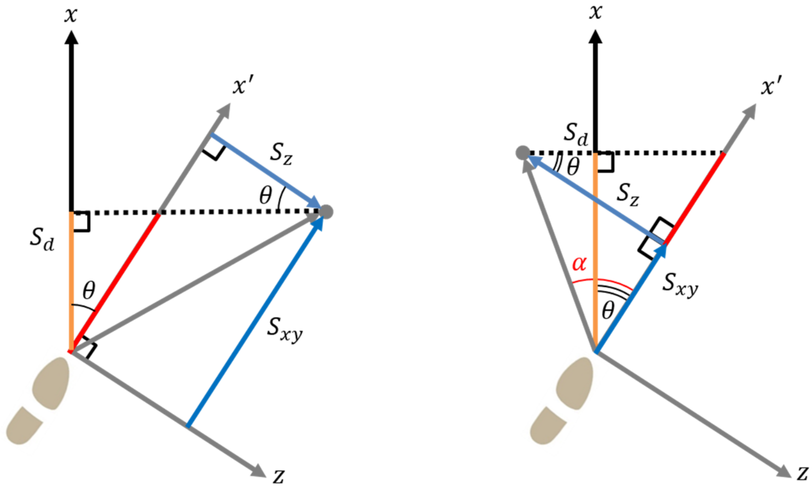


Figure 8. Geometrically analyzed synthesis method

The left of Figure 8 is the case where the balance was broken and the toe-out walker swayed his foot to outward lateral direction. In this case, the displacement vector S_z is positive. The angle θ is pre-measured toe-out angle. If we subtract tangent of S_z from the displacement S_{xy}, we can obtain the size of red vector. By multiplying cosine of this vector, we can calculate the size of displacement value of desired direction of gait. The right side of Figure 9 is the case when the toe-out walker restore the balance and return swayed foot to original course. In this case, the displacement vector S_z is negative due to its z axis. If we add the scalar value of dis S_{xy} and tangent theta of displacement S_z, we can obtain the scalar value of vector $S_{xy'}$. By multiplying cosine of this vector, we can calculate the size of displacement value of desired direction of gait once again. But the actual value of displacement vector S_z is negative, so equation can be expressed to one single equation (14).

$$S_d = (S_{xy} - S_z \times tan\theta) \times cos\theta \tag{14}$$

We generally use equation (13) for synthesis, but for certain case when size of S_z exceeds 50 percent of S_{xy}, we use equation (14) for synthesis. The equation (15) shows the condition and equation we use for synthesis.

$$\begin{cases} S_d = \sqrt{s_x{}^2 + s_y{}^2 + s_z{}^2}\ , & \left(S_z < \frac{1}{2} S_x\right) \\ S_d = \left(S_{xy} - S_z \times tan\theta\right) \times cos\theta, & \left(S_z > \frac{1}{2} S_x\right) \end{cases} \tag{15}$$

The mean velocity of one stride is estimated by dividing synthesized distance to stride time T.

$$V_{stride} = \frac{S_d}{T} \tag{16}$$

2.4 Excluding algorithm

To extract the targeted gait pattern, straight line walking, we need to classify the differences between various gait patterns. There are many types of walking pattern, but we categorize it into seven patterns. Those patterns are stop, straight line walking, inclined walking, declined walking, stair ascending, stair descending and unclassified other walking patterns.

First, we use stride time for excluding criteria. The average stride time for healthy adult is under 1.5s. Therefore, if the stride time exceeds more than 2s, the stride is definitely not a normal straight line walking. IF stride time was more than 2s and mean velocity was extremely low, we can assume that stride was occurred after stop. And if the stride time was long, but the velocity was extremely high, we can assume that walker was on elevator or other transportation method which does not move foot.

Second, we use inclination for excluding criteria. There are two different ways to calculate the inclination of the gait. First is using the inertial angular position calculated by arctangent of inertial foot-flat acceleration as described in equation (8). This inclination means that when the foot-flat occurred, foot was on the inclined surface in that moment. The second method is to calculate inclination using the tangent of x, y displacement. This inclination means that when the x displacement was occurring, start point and end point of the stride had y elevation displacement. Using this two inclination calculating method, we can define if the stride was on stair or ramp, and if it was ascent or descent.

Figure 9.A describes the behavior of human foot in ramp and stair walking. When the walker ascend the stair, the foot-flat occur horizontally, because the stair has horizontal surface. But still y axis displacement shows elevation of the foot. When the walker ascend the ramp, the foot-flat occur with inclination, due to the inclined surface of the ramp. And y axis elevation can be observed. We can notice the stair and ramp ascending walk from straight line walk using y axis elevation. And then we can classify the stair walk if the foot-flat is horizontal. If the y axis elevation occurred and foot-flat is inclined, the stride is ramp ascending.

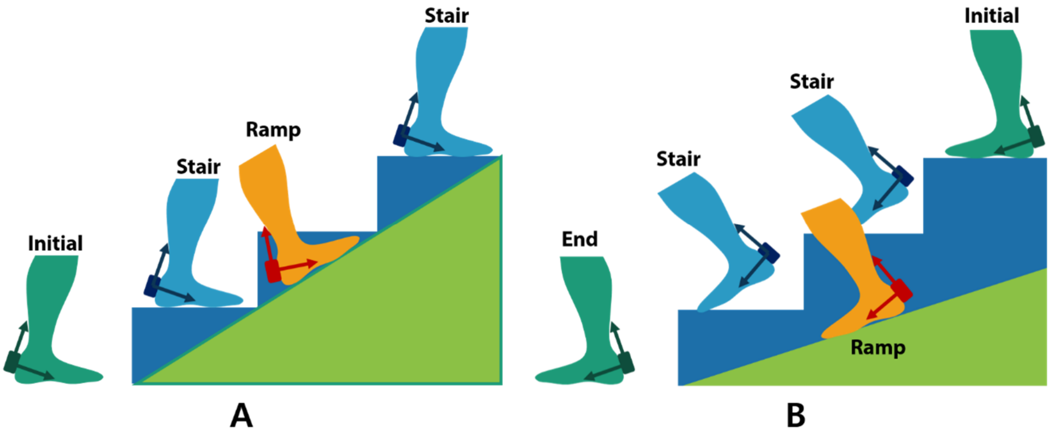


Figure 9. Description of foot behavior on ramp and stair. A: ascending, B: descending.

Fig. 9.B describes the descending behavior of human foot in ramp and stair. The negative elevation of the y axis shows both stair and ramp descending. Different from ascending, we cannot detect surface inclination properly due to kinematic characteristics of stair descending. We can detect inclined foot-flat on ramp descending, but it is difficult to detect horizontal foot-flat on stair descending. The reference [15] insist that stance phase of stair descending starts from plantar flexion of the ankle joint to toe-strike. The problem is, if the stair is continually long enough to make several steps, the walker steps without their heel strike on the ground. Therefore stair descending shows toe-stepping pattern, which is similar to declined foot-flat in the viewpoint of IMU. To compare stair and ramp descending, we need more specific threshold and conditions. But our primary target of excluding algorithms is to reject all other walking patterns except straight line walking, so despite the fact that we cannot define this negative elevation is either ramp or stair, it is still available to reject both patterns.

Table 1. Conditions for pattern recognition

Index	Foot-flat incline, $atan\left(\frac{a_t}{a_n}\right)$	Elevation incline, $atan\left(\frac{S_y}{S_x}\right)$	Stride Time (s)
Normal	Same with initial	None	T < 2
Incline	Positive	Positive	T < 2
Decline	Negative	Negative	T < 2
Stair Up	Same with initial	Positive	T < 2
Stair Down	Same with initial	Negative	T < 2
Stop or others.	-	-	T > 2

The conditions for pattern recognition is organized on Table 1. Our goal is to reject the most of the gait patterns except straight line walking. Therefore the main target is to find horizontal foot-flat with stride time under 2s and no elevation on y axis, which we classify as the normal walk. But in daily life, there are no surfaces which are perfectly horizontal. There are surfaces with small amount of inclination which doesn't affect much, and cause small amount of differences on kinematics of lower limbs. McIntosh, A.S. [16] suggest that inclination of 5 degrees cause significant amount of affect, so it is not negligible. As the 5 degree of inclination can affect a human body, it means that walking pattern is significantly changed for 5 degrees of inclination. That is the reason why we set threshold of 3 degrees to use small inclined walk under threshold for our preferred gait speed monitoring, and categorize any inclination over 3 degrees as inclined walk.

2.5 Validation of detecting the foot-flat

The gait cycle segment is the most crucial process to correctly estimate gait speed. The reason of the heel side attachment location of the IMU is to detect the foot-flat, a golden reference to determine if the foot is stopped during stance phase. The foot-flat occur when the foot stops instantly, so we detect foot-flat when the IMU has extremely low angular velocity for lateral axis, and when the synthesis of accelerations for each three axis is within the threshold of gravitational acceleration. The first experiment questions if this detection method is able to detect foot-flat regularly under these conditions.

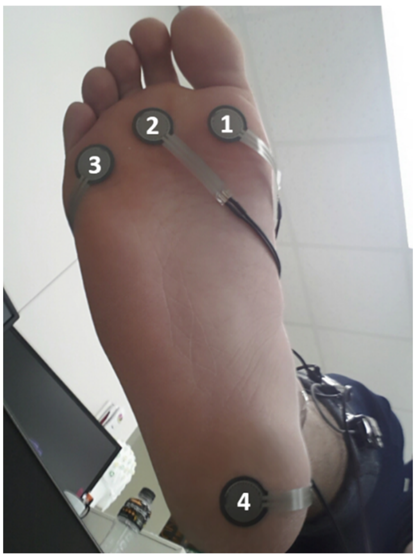


Figure 10. FSRs on foot. 1: First metatarsal, 2: Between second and third metatarsal, 3: Fifth metatarsal, 4: Heel

Subject was one healthy adult (Subject 0, male, age: 25, height: 181.8 cm, weight: 75 kg). The subject attached single IMU on heel side of the right foot and four FSRs on first metatarsal, between second and third metatarsal, fifth metatarsal, and heel of the foot (Figure 10.). Total three FSRs were attached below forefoot and one FSR was attached below rear foot.

The subject was asked to walk on the horizontal treadmill for three minutes, with self-selected preferred speed. The IMU and FSR data were measured simultaneously. The sampling rate of IMU was 204.8Hz, and sampling rate of FSR was 200Hz. We measured largest activation of the FSR when subject was standing on one foot, then we set minimum 5% of threshold of largest activation for confirmation of activation.

2.6 Validation of gait speed estimation for horizontal and inclined treadmill

The subjects were four healthy adults (Two male, two female, age: 26.6 ± 1.87, height: 168 ± 10.71cm, Table 2.). Subjects attached single IMU on right heel side of the foot for gait speed estimation. Subjects were asked to walk on treadmill for one and a half minute with four different speeds; 0.6m/s, 0.8m/s, 1.0m/s, 1.2m/s. Then the subjects were asked to walk on inclined treadmill with 1m/s of speed and three different inclinations; 3deg, 5deg, 10deg. The inclined treadmill also took one and a half minute for each walking trials.

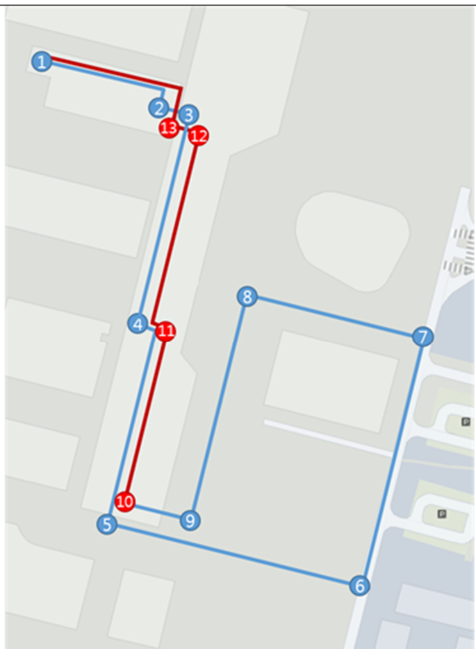
Table 2. Subject details

	Subject 1	Subject 2	Subject 3	Subject 4
Gender	F	F	M	M
Age	28	25	28	26
Height (cm)	152	174	174	172

2.7 Validation of gait speed estimation for long term gait

The same subjects from previous experiment were also asked to walk on predefined outdoor walking course. The course contains straight line walking, stair ascent and descent, ramp ascent and descent, and elevator up and down for four stories. The course distance was measured by digital walking counter, and rough inclination of the ramp was measured by digital protractor. (Figure 11.). The distance is 1112m, and the details of the course are organized in Figure 12.

Figure 11. Walking counter and digital protractor.



1~2 (Course 1)	Straight Line (SL)	82 m
2~3	Elevator, Door	26.7m
3~4	Curve + Straight Line	132m
4~5	Two sets of stairs	44.24 m
5~6	Outdoor, Decline	160.4 m
6~7	Incline	132 m
7~8	Incline + SL	97 m
8~9	SL + Decline	125.8 m
9~10	Indoor, SL	54 m
10~11	Two sets of stairs	44.24
11~12	SL + Curve	132 m
12~13	Door, Elevator	26.7 m
13~1	SL	82 m

Figure 12. Course outline and Explanation.

The course starts following the blue line. From point 1 to point 2 is the course 1, which is straight line corridor on Sixth floor. After the course 1, the subjects ride elevator to third floor. There, they pass the gate and meet another straight line corridor. After the corridor is passed, there are two stories of stairs. The stair 1 has 27 stairs of depth with 0.31 meters and 5.8 meters of space in the middle of the stairs. The stair 2 has 27 stairs of depth with 0.31 meters and 3.4 meters of space in the middle of the stairs. The distance between two stair sets are 18.5 meters, and the summation of the distance is approximately 44.24 meters. After the stairs, the subject head outside of the building. There are some straight line and decline. The decline has negative 3 ~ 6 degrees of inclination. The inclination is not uniform and the ramp is curved so mean inclination is difficult to calculate. When the subject pass point 6, the incline starts. From point 6 to point 7, the average inclinations is approximately 4.5 degrees and it is more even than the decline course. The last few meters between point 6 and 7 contains straight line. From point 7 to 8 has slight inclination and mostly horizontal surface. Next there are another decline between 8 and 9. The decline angle is negative 4~6 degrees of inclination. This ramp is also curved, but the most of the angle is near negative 5 degrees. After the decline the subject pass the gate into indoors, and follow the same path to return to the start point. The course contains all conditions; straight line, ramp ascent and descent, stair ascent and descent, elevator, and door opening. The main purpose of long term gait measuring is to separate straight line walking pattern from other patterns and extract the preferred gait speed of the subject on straight line walk.

The course was slightly modified before the last two subjects walked. We put 77.85m long taped walkway during the course 1 for validation of outdoor gait speed estimation. Because there are no significant method to measure the gait speed of subjects outside the gait-lab, comparing the real distance and calculated distance using estimated average velocity becomes the validation method. We measured the taped walkway for several times to be sure of its distance. The total distance of entire course was maintained.

III. Result

3.1 Validation of detecting the foot-flat

The subject 0 walked with preferred speed of 1.0 m/s for three minutes. The result of detection is Figure 13.

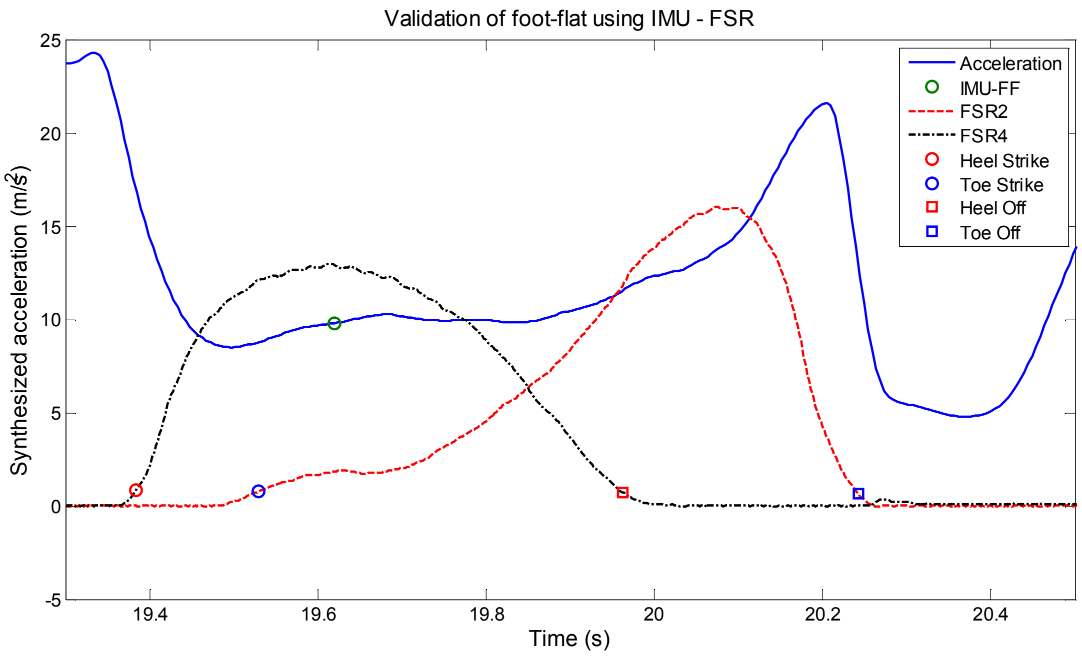


Figure 13. Validation of foot-flat using IMU and FSR for single foot.

The blue line shows the synthesized accelerations. The green circle on the acceleration curve express the detected foot-flat. The red bar line is the amplitude curve of FSR 2, which was attached between second and third metatarsal. As the foot-flat is when the entire foot is horizontally contacted to the surface, it occurs between toe-strike and heel off. We assumed the contact of FSR 2 is toe-strike, which is the start point of the foot-flat. The toe strike is expressed by blue circle on the red bar curve. The black bar-dot curve is the amplitude curve of FSR 4, which was attached below the heel. We can find the end point of foot-flat on heel off, the red square on the black bar-dot curve. The time value of detected foot-flat in Figure 13 was 19.62 seconds, and toe strike was 19.53 seconds. The error was within 0.09 seconds. The average error between toe strikes and detected foot-flats were 0.0997 seconds for standard deviation of 0.0329.

3.2 Validation of gait speed estimation for horizontal and inclined treadmill

Four subjects walked on treadmill before their long term gait. The Figure 14 shows gait speed estimation graph for horizontal and inclined treadmill walk. The left column shows their gait speed estimation on horizontal treadmill for various speeds. There are some errors and deviations, but we can easily find the differences between various speeds. The right column shows result of inclined treadmill walk. The treadmill speed was same at all trial for 1.0 m/s, and the graphs of walking speeds are gathered around the treadmill speed. The gait speed estimation on inclined treadmill was also successful with minor errors. The Figure 15 shows the estimated incline angle of inclined treadmill walk. The results are organized in Table 3 and Table 4.

Table 3. Estimated gait speed of four subjects

Inclination (deg)	Treadmill Speed (m/s)	Subject 1 (m/s)	Subject 2 (m/s)	Subject 3 (m/s)	Subject 4 (m/s)	Average Error (m/s)
0°	0.6	0.6037	0.6340	0.5986	0.6047	0.0109
	0.8	0.8002	0.8463	0.8069	0.8153	0.0172
	1.0	0.9889	1.0204	1.0420	0.9994	0.0185
	1.2	1.2076	1.1630	1.1943	1.197	0.0133
3°	1.0	0.9682	1.0069	1.0035	1.0141	0.0141
5°	1.0	0.9602	0.9972	1.0518	1.0597	0.0385
10°	1.0	0.9580	0.9755	1.0402	1.0251	0.0330

Table 4. Estimated treadmill incline of four subjects

Treadmill Inclination (deg)	Subject 1 (deg)	Subject 2 (deg)	Subject 3 (deg)	Subject 4 (deg)	Average Error (deg)
3°	4.88	4.82	4.4452	3.3989	1.3860
5°	5.75	5.0763	5.52	5.5299	0.4691
10°	10.0704	11.5056	10.6218	10.8810	0.7697

The largest error in gait speed estimation was 0.0597 m/s for subject 4, in 5° inclination. The smallest error was 0.0002 m/s for Subject 1, 0.8 m/s belt speed. The mean error for entire speed estimation was 0.0208 m/s. The largest error in incline estimation was 1.88 for subject 1, 3° inclination. The smallest error was 0.0763 for subject 2, 5° inclination. The mean error for entire incline estimation was 0.8749°.

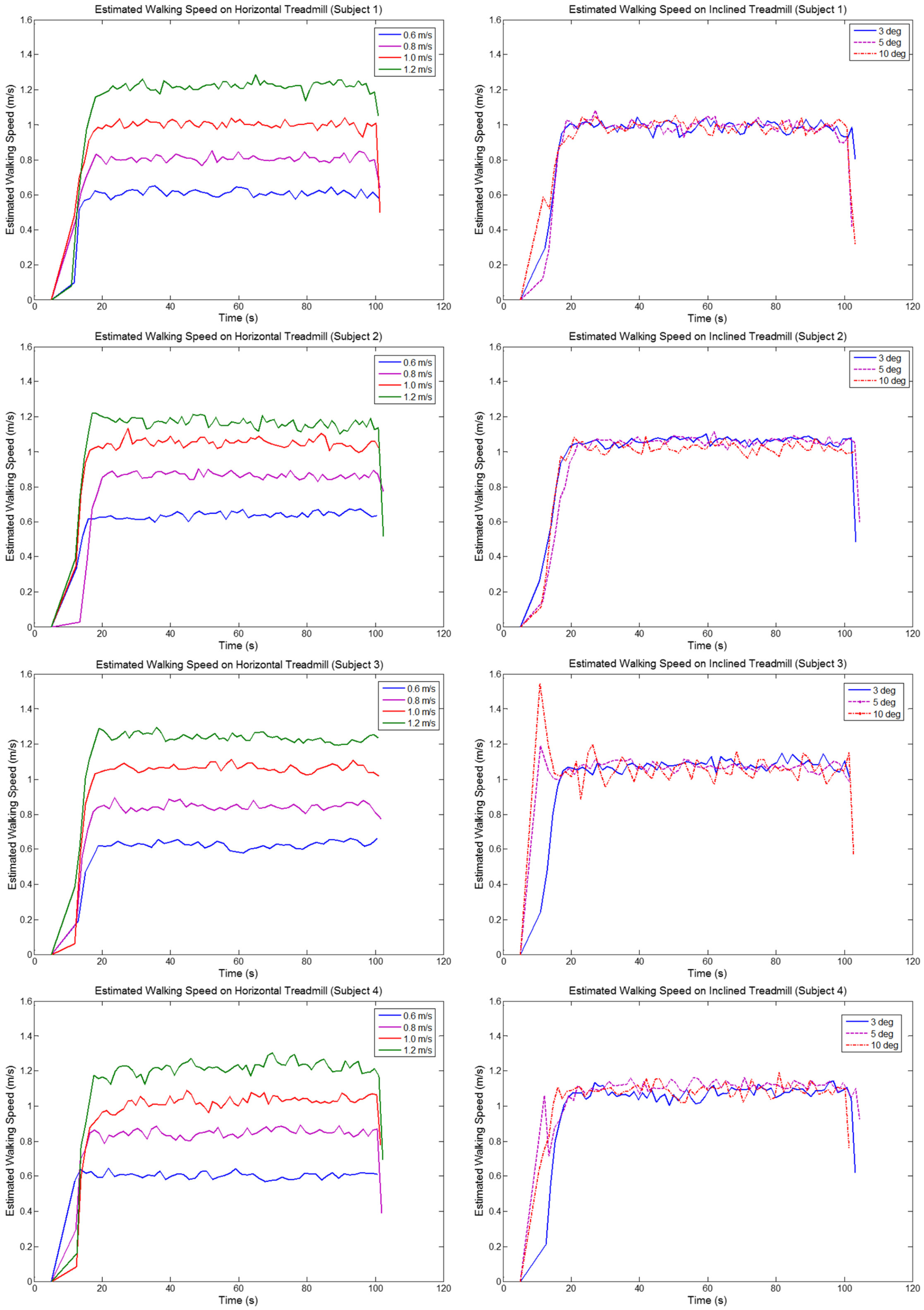


Figure 14. Treadmill walking gait speed estimation of four subjects including horizontal and inclined treadmill walk

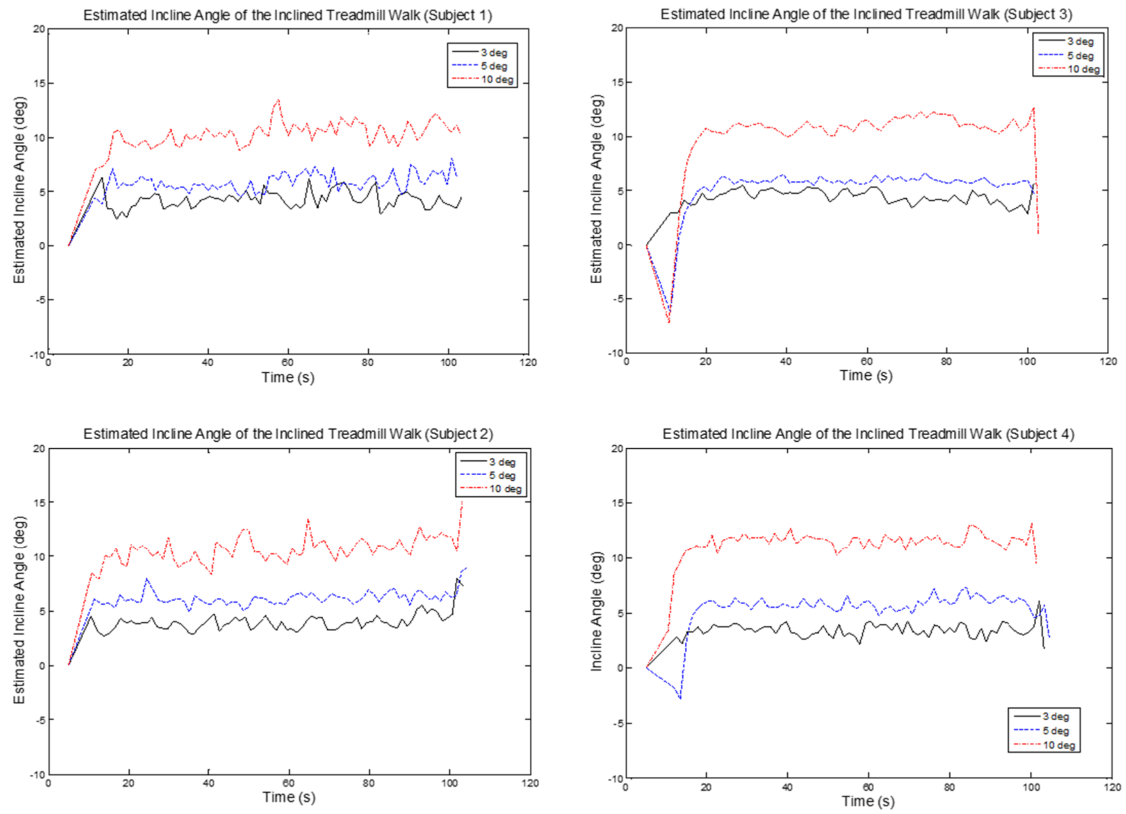


Figure 15. Inclined treadmill walking incline estimation for four subjects

3.3 Validation of gait speed estimation for long term gait

The speed estimations of four subjects are shown in figure 16. The Black line is estimated gait speed for each segmented strides. The recognized gait pattern of each stride is represented with colored marker. The red circle is our targeted preferred walking as called as the normal walk. The blue circle and cross refers to ramp ascent and descent. The green circle is stair ascent. All other patterns such as stop, stair descent, and elevators are categorized as the others, and expressed in black circle. All timings of gait events were compared with recorded video.

The problem of verifying long term gait speed estimation is that even if the each subjects walked on same path, it does not mean they walked exactly the same distance with measured outdoor course. Our measured course is practically a guideline, not the exact answer. Therefore, we tried to set a verifying course inside the entire long term walking course. The verifying course was set on course 1, with straight line course of 77.85m, measured precisely for several times. This verifying course was adapted with subject 3 and subject 4. The estimated values are organized through Table 5 and 6.

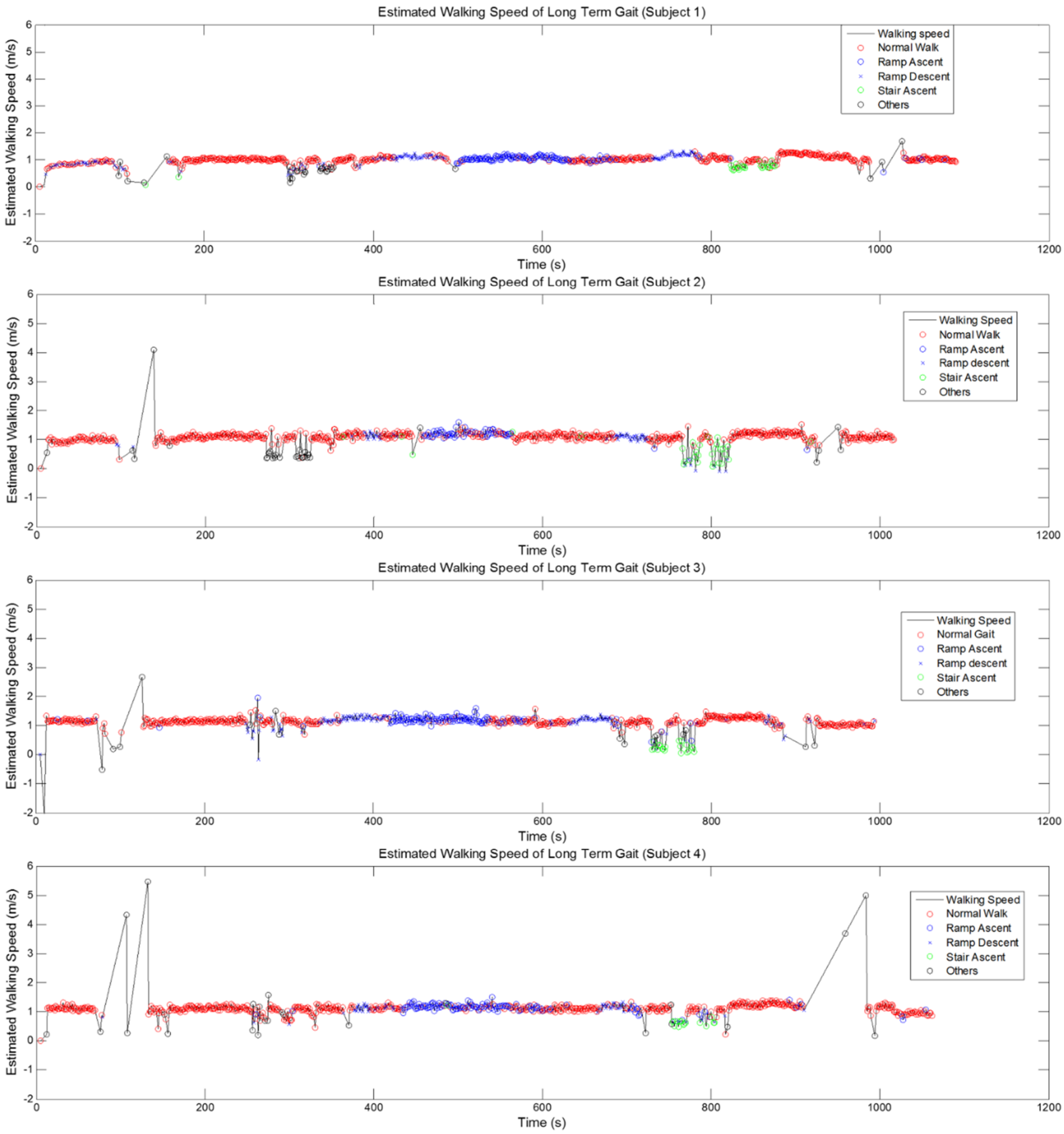


Figure 16. Long term gait speed estimation of four subjects

Table 5. Estimated values from long term gait

Estimations and error	Subject 1	Subject 2	Subject 3	Subject 4
Normal gait speed (m/s)	1.0218	1.0570	1.0927	1.1823
Ramp incline (deg)	4.1694	4.1624	4.2764	4.2065
Ramp decline (deg)	-5.6181	-5.0348	-5.8101	-5.7025

Table 6. Validation of outdoor walking speed estimation

Estimations and error	Subject 3	Subject 4
Actual Distance of taped course (m)	75.85	75.85
Time spent during taped course (s)	70.01	65.49s
Calculated mean walking speed on taped course (m/s)	1.0834	1.1582
Estimated Gait speed on taped course (m/s)	1.1045	1.1957
Estimated Distance of taped course (m)	77.3260	78.3064
Distance error of taped course (m)	0.5240	0.4564
Gait Speed error on taped course (m/s)	0.0211	0.0375

The mean estimated incline of the ramp ascent was 4.2037 ± 0.0522 degrees. The mean estimated decline of the ramp was -5.5414 ± 0.3467 degrees. The gait speed estimation of subject 3 and subject 4 was verified by verifying course which was 77.85m. The estimated walking distance of the taped course was 77.3260m and 78.3064m for each subjects, and the error was 0.5240m and 0.4564 for each subjects. The mean walking speed of course 1 was calculated by actual distance of the taped course and time spent during the taped course measured by video recording. The mean error of gait speed on taped course was 0.0211m/s and 0.0375m/s for each subjects.

IV. Discussions

4.1 Validation of detecting the foot-flat

The detection of foot-flat occurred between the toe strike and heel off. Which fits the condition of foot-flat from [14].There are slight delay between toe strike and foot-flat. The delay is due to second order Butterworth low pass filter. If the cutoff frequency of the filter gets high, sooner the foot-flat will be detected. The accuracy is not important since the foot-flat detection is regularly occurred. Regularity is the key value for foot-flat detection because we use foot-flat to divide the gait cycle, in time shifted acceleration and angular velocity data. As the delayed foot-flat is still located between actual foot-flat period, and the amount of delay is short as 0.1s, our analysis does not seriously affected by time shift.

4.2 Validation of gait speed estimation for horizontal and inclined treadmill

The result of walking speed estimation on treadmill was successful. As we assume the treadmill is golden reference of the gait speed, errors were small enough to neglect. Average velocity of treadmill gaits were calculated without stride velocities from the first few strides and the last few strides (acceleration and deceleration). As our algorithm need few seconds of initialization at the beginning of the gait, the subjects had to stand on a horizontal surface before treadmill walking. When the treadmill had zero incline, it was fine for subjects to start initialization on the treadmill. But when the treadmill was inclined, subjects had to perform initialization on the ground and then stepped up to the treadmill. The 10 degrees inclined gait speed estimation of subject 3 shows the pattern of large velocity peak at the beginning. The peak happened in first step, when the subject stepped on the inclined treadmill with left foot, and swing the right foot for higher advance. The subject had a sudden fast swing to move his foot on the treadmill, so the great amount of acceleration occurred and it was integrated into velocity peak. Other subjects stepped their right foot slow and steady so there was no velocity peak observed.

Despite the gait speed estimation was accurate, the estimation of inclined angle had some errors. Especially, when the treadmill was inclined for 3 degrees (5.24% Inclination), the error was up to 1.88 degrees. We calculate the inclination data using the instant acceleration when the foot-flat occurs, so the cause of the error is acceleration only. This phenomenon might be occurred by the accelerometer error, which might be occurred after the low pass filter. To lessen the noise and errors, further study of enhancing the angle estimation is required.

4.3 Validation of gait speed estimation for long term gait

The long term gait measuring was performed both indoors and outdoors. The inclination of indoors were near zero for every course. But the outdoor had rough surface that inclinations were not uniform. The ramp of the surface was curved and the surface was using brick sized concrete blocks as finishing material. Each concrete blocks had different inclinations and by mixing up with curved ramp, it was difficult to measure exact inclination of entire course. The estimated incline and decline of Table 5 is mean inclination of each strides performed on ramps included in course. The estimation was acceptable for ramp ascent and descent. The estimations of inclination has small standard deviation of 0.3467 degrees.

The recognizing algorithm used with the threshold of 3 degrees, so every walk which defined as inclined walk, was performed on the ramp inclination over 3 degrees or less than -3 degrees. Because of this threshold, minor ramps under threshold was neglected.

Detection of the stair descent contains tradeoffs because of its toe-stepping characteristics. Every subjects who were in this study walked with their toe only during the stair descent as shown in figure 9.B. Therefore both ramp descent and stair descent contained both acceleration based inclination and displacement based inclination. The difference is in between the amount of inclination, but this difference was not uniform since the toe-stepping of stair descent didn’t have apparent patterns.

Some gait patterns had difficulties with detecting, but still our target is to exclude them and analyze the gait speed of the straight line walking on horizontal surface, as called as normal walk. The normal walk can be easily detected, and therefore our goal of excluding was achieved. The speed estimation was verified by taped straight line course in the course 1, which is 77.85 meters long precisely. The timing was checked by video clips we recorded during the long term trial. The result organized in Table 6 suggests that the gait speed estimation of the outdoor straight line course was successful with error within 0.04 m/s.

The future of long term gait speed estimation is to perfectly recognize the each gait patterns in order to use not only their straight line walking, but also the various gait patterns for clinical analysis.

4.4 Other discussions

After the long term measuring, the position of the IMU was questioned. By the toe-stepping characteristics during the stair descent, it was difficult to detect the stair descent, so we simply exclude every negative inclination except the ones near threshold. The heel side IMU location can be an obstacle for distinguishing stair descent from ramp descent. Additionally, some user might feel discomfort during the stair descending due to its location. The IMU might fall off if the user walk when their heel side is close to the stair edges. The main reason of heel location was to assure the horizontality of z-axis. The IMU attached on lateral side of the foot has tilt of z-axis because the lateral side of the foot is inclined. And toe is unconsidered because the user can kick the IMU and cause a damage to the unit. Therefore the additional candidate for IMU location is upper side of the foot. But the upper side of foot has less sensibility than heel side, because of its medial position between heel and toe. But still, the safety and accessibility to foot-flat and inclination of the surface has potential feasibility.

The large peaks in Figure 16 are integrated elevator speed. There are difference between the speeds of elevator for each subjects. The reason of the difference is if the subject moves during the zero-acceleration movement of the elevator, the additional summation of acceleration or deceleration can be added. The detailed acceleration pattern of the elevator is like figure 17. The acceleration occurs for few seconds and elevator moves in same velocity. Before it stops the deceleration occurs. Between the acceleration and deceleration, there is zero acceleration period. When the subject steps during this period, the velocity will be reset to zero and deceleration will cause additional velocity.

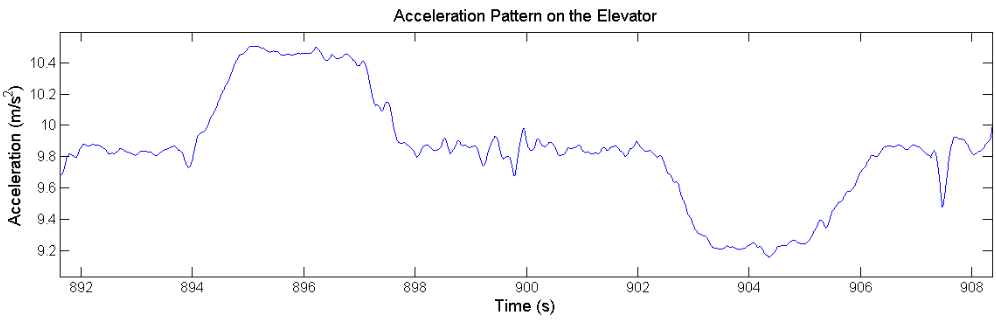


Figure 17. Acceleration pattern on the elevator

V. Conclusion

5.1 Conclusion

The heel side mounted IMU was able to detect the foot-flat as we assumed it is instant stop. By detecting the foot-flat, a fine beacon for gait cycle segmentation, we were able to estimate walking speed and the instant inclination of the foot, which varies on the inclination of the ground surface. The gait speed estimation on the treadmill was successfully available, and our interest was to estimate the gait speed outside the gait-lab.

The first step to long term monitoring of gait speed, was to walk on long outdoor course and estimating the gait speed of the straight line walking. To exclude other gait patterns except the straight line flat surface walking, we used stride time, acceleration based instant incline, and displacement based calculated incline as categorizing criteria. These values were able to obtain due to foot-mounted IMU.

The categorizing was successful without stair descent, which has complex arguments to deal with our criteria. But the goal of this study was to extract the normal gait only to estimate the preferred walking speed of the subjects. The walking speed of the subjects were verified using accurately measured straight line walkway.

5.2 Future work

For the future work, we would like to enhance the incline estimation using accelerometer. There are some errors with low angle estimation, and the problem is not crucial for calculating the walking speed. But if we approach to clinical analysis of various walking patterns including incline walk, we need to estimate the incline angle accurately. Also, there was problem detecting the stair descent accurately using current algorithm. To perfectly categorize the stair descent and ramp descent in order to use other gait patterns for clinical analysis of long term measurement, we need to adapt more basic pattern recognition methods like using the curve pattern of acceleration or angular velocity of the foot during the stair descent.

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요 약 문

한 개의 Inertial Measurement Unit 을 사용한 일상 생활에서의 장기간 보행 속도 관찰 시스템

Inertial Measurement Unit(IMU)을 사용한 보행 속도의 추산은 인력의 낭비 없이 일상 생활에서 사용하기에 적합한 방법이다. 한 개의 IMU 를 발 뒤꿈치에 부착함으로써, 우리는 사용자의 보행 속도를 추산할 수 있다. 이 기능을 일상 생활에 적용하기 위하여, 우리는 장시간 동안의 보행 속도 추산을 목표로 하고 있다. 본 논문은 일상 생활에서 발생하는 여러 종류의 보행 패턴 중에서도 특히 직선 보행에 초점을 맞추고 있다. 보행 속도를 추산하기 위해서는 보행을 순환 주기에 따라 분할하여 IMU 의 드리프트 에러를 줄여야 한다. 본 논문에서는 보행 주기를 보행의 확고한 현상인 foot-flat 을 이용하여 분할하고 있다. 첫째로, IMU 의 foot-flat 포착을 검증해야 한다. 한 명의 대상이 한 개의 IMU 와 force sensing resistor 를 한 발에 부착하고 treadmill 위를 선호하는 속도로 걸어, 두 장비의 foot-flat 포착을 검증하고자 했다. 두 번째로, 네 명의 건강한 성인 대상들(2 남 2 녀)이 treadmill 위에서의 속도와 경사도 추산을 검증하는 실험에 참여했다. 마지막으로 네 명의 건강한 성인 대상들이 장기간 보행에서 계단 오르내림, 경사로 오르내림 등의 다양한 패턴들을 제거하는 알고리즘을 검증하는 실험에 참여했다. 장시간 보행에서 수평적인 지면에서의 보행만을 추출함으로써, 우리는 사용자의 선호하는 보행 속도를 얻을 수 있다. Treadmill 에서의 보행 속도 및 장기간 보행에서의 보행 속도 추산은 성공적이었으나, 계단의 패턴을 정확하게 인식하는 부분에 있어 추가적인 연구가 필요하다.

핵심어: Inertial Measurement Unit, 장기간 보행, 선호 보행속도, 일상 생활.