# Walking Motion Analysis of Intermittent Claudication and its Application to Medical Diagnosis

# Walking Motion Analysis of Intermittent Claudication and its Application to Medical Diagnosis

Tetsuyou Watanabe, Yui Sanou, Takeshi Yoneyama,
Yasumitsu Toribatake, Hiroyuki Hayashi and Noriaki Yokogawa

***Abstract*— There are mainly two kinds of diseases in intermittent claudication. One is lumbar spinal canal stenosis (LSS) and the other is peripheral arterial disease (PAD). Differentiating LSS and PAD is a critical issue. Wrong differentiation might cause amputation of lower extremities. At small clinics and hospitals, simple and cheap differentiation system is required. Concerning this, this paper investigated walking motions of the patients. The subject with LED markers walked on the treadmill until she or he felt pain. We recorded the walking motion by camera and tracked the LED markers. Treadmill enables to measure walking motion for a long time in a small space, and LED marker provides position of every joint in the walking. Then, we can get the information such as joint angle trajectory, hemi-foot step, stance and swing phases without any other sensors like foot switch or force plate. We compared walking motions of healthy persons, LSS patients and PAD patients, found their features and 3 factors for disease differentiation; average bending angle of knee joint at the start of stance phase, average dorsiflexion angle of ankle joint, and average hemi-foot step length. The results indicate that 2 dimensional images of walking motion for several seconds are enough for deriving the factors. Then, we can construct the simple examination system for the disease differentiation.**

## I. INTRODUCTION

INTERMITTENT Claudication [1] is a walking symptom defined that the patients cannot continue walking due to algia or numbness of lower limbs after walking for some period, but if they take a rest, they can walk again. We are approaching to aged society. Then, recently there has been a marked increase in the number of patients who consult a doctor of orthopedic surgery due to the intermittent claudication [2]. Roughly speaking, there are two kinds of main problems for intermittent claudication: LSS (lumber spinal canal stenosis) and PAD (peripheral arterial disease). These diseases are definitely different diseases. Therefore it is clinically very important to differentiate the main problems. If the doctor missed the diagnosis and the patient were cared for according to the wrong diagnosis, the patients would suffer from necrosis or paralysis of lower limbs, or vesicorectal disorder. The medical treatments of LSS patients are done by the doctors of orthopedic surgery while the treatments of PAD patients are done by the doctors of vascular surgery or cardiovascular internal medicine [1].

T. Watanabe, Y. Sanou and T. Yoneyama are with the College of Science and Engineering, Kanazawa University, Kakuma-machi, Kanazawa, 920-1192, Japan (corresponding author to provide phone: +81-76-234-4682; fax: +81-76-234-4682; e-mail: twata@t.kanazawa-u.ac.jp).

Y. Toribatake, H. Hayashi and N. Yokogawa are with the Department of Orthopedic surgery, Koseiren takaoka Hospital.

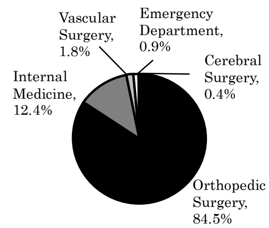



Fig.1. Specialty of the doctor whom the patients of intermittent claudication consult at the first time

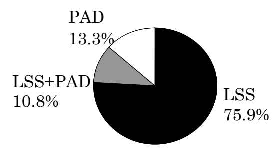



Fig.2. Main problem of the patients of intermittent claudication who consult orthopedic surgeon.

However, the intermittent claudication is a kind of walking trouble, and then most of the patients firstly consult the doctor of orthopedic surgery as shown in Fig.1 [3]. As shown in Fig.2, the main problem of about 13% of the patients who consult orthopedic surgeon was reported to be PAD [3]. Therefore, it is critical to distinguish PAD and LSS in the medical diagnosis at orthopedic surgery clinics. In Japan, the number of LSS patients is larger than the number of PAD patients while in western countries, the number of PAD patients is larger. However, if taking aging population and westernization of dietary habit into consideration, the number of PAD patients is considered to be large in future in Japan [3].

So far, there are several methods for the differentiation: examination by touch or observing standing posture, and examination through large precision instruments such as angiography, myelography, and MRI (magnetic resonance imaging). However, with the former examination, the doctors sometimes can not identify its main problem. On the other side, the latter examinations are invasive and high cost, and only professionals can use such precision instruments. Then, it is difficult to conduct such a high cost examination at small hospitals and clinics. From the viewpoint of the patients, the high cost is not undesirable.

Concerning the above, this papers aims at developing an examination system which can differentiate PAD and LSS easily and with low cost, and which can be used even at small hospitals and clinics, by using walking motion analysis. The main contributions of this paper are as follows.

1. Extraction of factors to differentiate PAD and LSS: By analyzing the walking motion, we extract 3 new factors to differentiate PAD and LSS.

2. Walking motion measuring method for the differentiation: Based on the experimental results, we show that we only have to observe walking motion for a few seconds to differentiate PAD and LSS. This is good news for the patients suffering from intermittent claudication since they can stop walking before feeling pain at their legs.

3. Simple walking motion measuring system: The subjects with LED markers walk on the treadmill. The walking motion is recorded by commercially available digital cameras. The obtained motion image is analyzed to differentiate PAD and LSS. Generally, special markers and cameras are needed for motion capture system. In addition, many numbers of cameras and large space are needed to capture walking. However, it is difficult to provide such special instruments and large space at small hospitals and clinics. We use simple handmade LED markers, measure only one side of the patient by camera and do not use the other sensors such as footplate. The obtained motion image doesn't have 3 dimensional information but, we show 2 dimensional motion image has enough information to differentiate PAD and LSS. Then, we can develop the measuring system which can be used easily and with low cost by the doctors at small clinics who is not professional for engineering or technology.

From half a century ago, there are researches concerning with walking motion; for example, walking pattern analyses for normal men [4] and women [5], estimation of human position at indoor [6], measuring joint moment of lower limbs when the subjects attach artificial legs [7], analysis of walking pattern of the patients suffering from osteoarthritis of hip [8], and analysis of the long-term walking motion of the patients whose hip totally replaced with artificial one by operation [9], analysis of epidural pressure in patients with lumbar spinal stenosis [10]. However, the walking motion analysis for main problem identification of intermittent claudication has not been done yet. We aim at developing simple walking motion analysis system and at differentiating PAD and LSS.

## II. WALKING MOTION MEASUREMENT AND ANALYSIS SYSTEM

### *A. Measurement system*

As shown in Fig.3, we attached handmade LED markers on the subject. We turned off the room lights so that only the lights of the LED markers could be seen. Every subject walked on the treadmill until she or he felt pain at her or his leg. The merit of using treadmill is that 1) we can measure even in a small room, 2) we can record long-term walking motion with a few cameras (we do not need a lot of cameras), 3) we can fix the camera position and then stable motion image can be obtained. On the other side, the drawback of using treadmill is that the walking could be different from

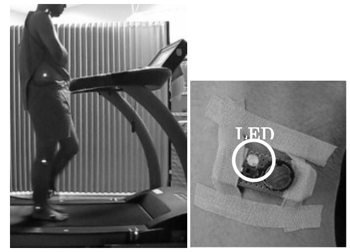



Fig.3. LED markers on the subject

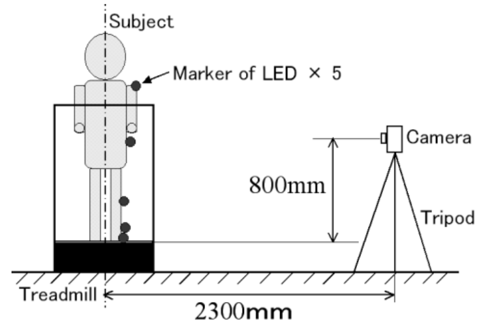
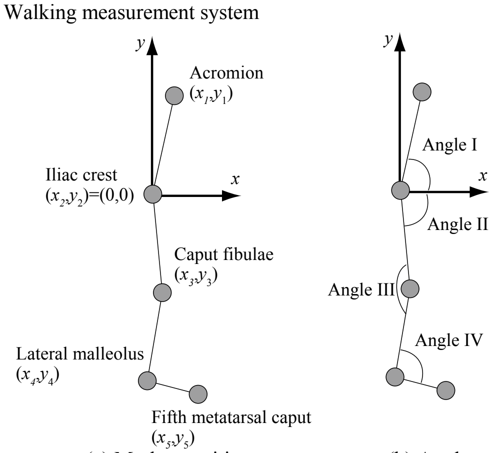



Fig.4. Walking measurement system




(a) Marker positions (b) Angles

Fig.5. Coordinate frame, marker positions, and angles

normal walking on the floor. In this paper, we have to develop the measurement system which can be used even in small clinics where it is hard to provide the room specially set up for motion capture. Then, we will take this way.

Fig.4 shows the detail of the system. The camera is placed 2300 [mm] away from the subject. We only recorded either left or right side of the walking posture. We put LED markers on acrominon, iliac crest, caput fibulae, lateral malleolus and the 5th metatarsal caput of the subject. Hereafter we call the 5 LED markers Marker 1, Marker 2, Marker 3, Marker 4, and Marker 5 in the order listed before. Fig. 5 (a) shows the definition of the coordinate frame and the marker positions. Note that the right side is assumed to be forward direction in Fig.5. Here is the reason why we used the 5 markers and their positions:

--First, we can detect the corresponding bone positions in spite of the existence of the skin, and then we can easily and relatively accurately attach the markers on the desired positions.

--Second, 5 is the minimum number to get the information

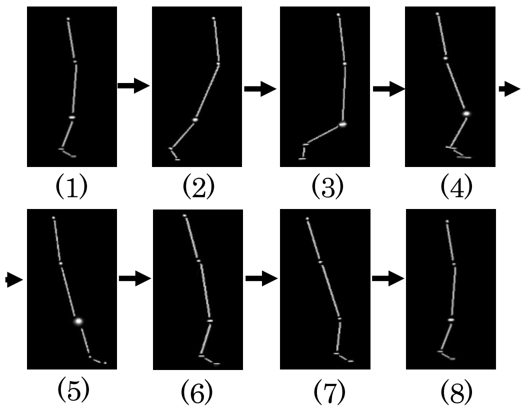



Fig. 6. Captured walking motion in one cycle

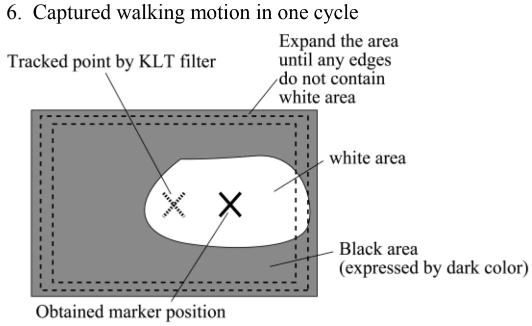



Fig. 7. Estimated marker position based on the tracked point by KLT filter

about the angles of the hip, knee, and ankles. Note that rigorous accurate angles are not necessary, but angle information for differentiating the diseases is needed.

### *B. Method*

The LED markers were attached on the leg where the patient has disorder. The subjects walked on the treadmill in semidarkness so that only the lights of the LED markers can be captured by the camera. Before the experiment, the subjects took a practice to walk on the treadmill. This practice included the two purposes: getting used to walk on the treadmill for safety, and setting the speed of the treadmill. We decided the speed so that the subject can normally walk. If the subject felt pain, then we stopped the measurement. If the subject did not feel pain, the subject walked for 10 minutes. Fig. 6 shows the overview of the captured walking motion image for healthy person. It corresponds to one cycle of the walking. The subjects are 13 normal healthy persons (4 males and 9 females), 15 LSS patients (8 males and 7 females), and 8 PAD patients (7 males and 1 females).

### *C. Deriving marker positions*

We got the image in which the areas around the markers were white and the other areas were all black. Then, by tracking the white areas, we got every marker positions. Fig.6 shows the images in which the marker positions (feature points) are connected by while lines.

The detail procedure is as follows. Firstly, using KLT filter [11], we detected the positions near the markers.

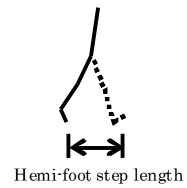



Fig. 8. Definition of hemi-foot step length

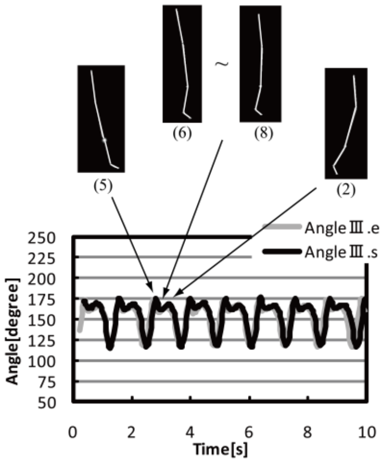
Unfortunately, the white areas were not constant but varied due to, for example, the change of the subject motion speed, and reflection of the LED light off the treadmill. Therefore, the tracked point by KLT filter did not always coincide with the center of the white area. Then, we recalculated the center position of every white area, based on the tracked points. First, we set the quadrangle area around the tracked points. Then, we extended the area size until the all edges of the area did not include the white area. Then, we got the quadrangle area which had only one white area. We calculated the geometrical center of the white area in the quadrangle area. It is the obtained marker position (see Fig.7).

### *D. Derived data*

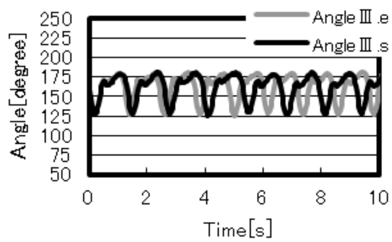
*1) Angle:* As shown in Fig.5 (a), we used the relative coordinate whose origin is located at Marker 2 attached on iliac crest. We derived Angle I, Angle II, Angle III and Angle IV as shown in Fig.5 (b). Angle I is the angle between x axis and upper body (the link belonging to half plane $y \geq 0$). It corresponds to the anteverted angle of the upper body. Angle II is the angle between x axis and the lower body (the link belonging to half plane $y \leq 0$ and connecting to Marker 2). It corresponds to the bending angle of hip joint. Angle III corresponds to the bending angle of knee joint. Angle IV corresponds to the dorsiflexion angle of ankle joint. Note that these angles are not completely identical to joint angles, but they are enough for disease differentiation.

*2) Stance and swing phases:* We present the way to derive stance phase starting time and swing phase starting time from only the captured images (without any other sensors such as foot switch or force plate). We focus on the motion of Marker 5 attached on the 5th metatarsal caput. We consider the time when the $x$ component of the 5th metatarsal caput position is maximum (the moving direction is $x$ direction), namely when the foot reaches its most forward position. We define the time is the stance phase starting time. We also consider the time when the $x$ component of the 5th metatarsal caput position is minimum, namely when the foot reaches its most backward position. We define the time is the swing phase starting time.

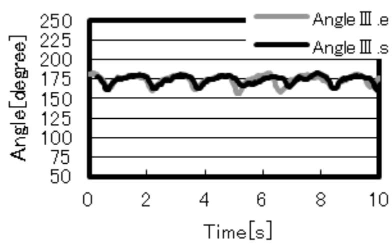
*3) Hemi-foot step length:* Fig. 8 shows the definition of hemi-foot step length. Note that in Fig. 8 walking motion is assumed to be captured from the right side of the subject, and then the right side is forward. The dot line in Fig.8 expresses the right leg in the case when it lands on the belt of the treadmill (stance phase starts). The solid line expresses the right leg in the case when it leaves from the treadmill (swing phase starts). We define the hemi-foot step length as the distance that the foot (Marker 5) moves on the treadmill in




(a) Normal

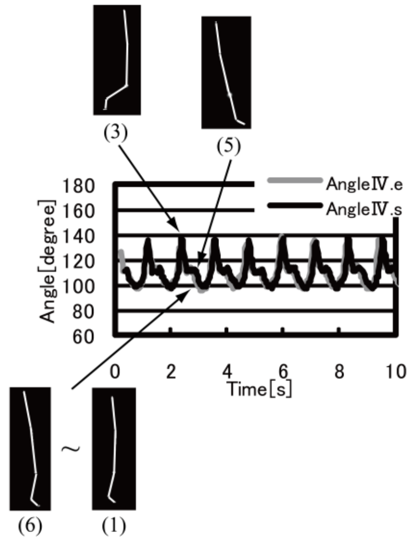



(b) PAD

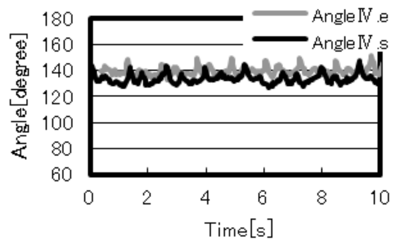



(c) LSS

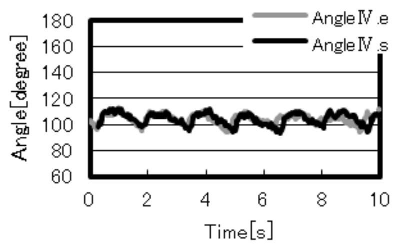
Fig. 9. Angle III




(a) Nromal

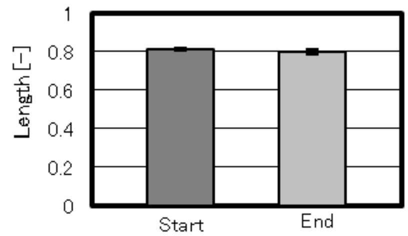



(b) PAD

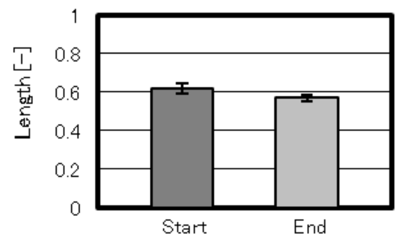



(c) LSS

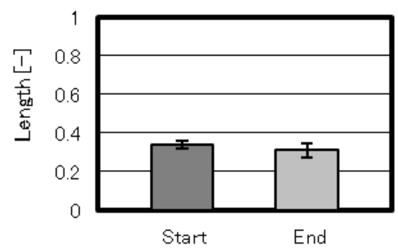
Fig.10. Angle IV




(a) Nromal




(b) PAD




(c) LSS

Fig.11. Hemi-foot step length

one cycle. We normalized hemi-foot step length with the leg length (the summation of the length between Marker 2 and Marker 3 and the length between Marker 3 and Marker 4). We derived hemi-foot step length by using the position of Marker 5 at stance and swing phase starting times.

## III. RESULTS

Fig. 9, Fig. 10 and Fig. 11 show the experimental results for representative subjects, in which the features we found appeared saliently (Later we show we got statistical significant difference with respect to the features). Fig.9 shows the time-series data for Angle III corresponding to the bending angle of knee joint. (a) is for normal healthy subject. (b) is for PAD patient. (c) is for LSS patient. Fig 10 shows the time-series data for Angle IV corresponding to the dorsiflexion angle of ankle joint. Fig.11 shows the average values for hemi-foot step length. In Fig. 9 and Fig. 10, the black lines express the derived data from the walking motion for 10 seconds just after the walking starts while the grey lines express the derived data from the walking motion for 10 seconds just before the walking stops. In Fig.11, *Start* and *End* denote the average values of hemi-foot step lengths for 10 seconds just after the walking starts and before the walking stops, respectively. Since intermittent claudication is a disorder that patients feel pain at their leg after walking for a while, we compared the data just after the walking starts with the data just before the walking stops.

### *A. Bending angle of knee joint*

Here, we discuss the data of Angle III corresponding to the bending angle of knee joint shown in Fig. 9. As shown in Fig.9 (a), the wave form for normal healthy person includes a wave form like the letter M, which means there are two local maximum and one local minimum values. It reaches its first local maximum when the foot lands on the treadmill (corresponding to the start of stance phase and the posture

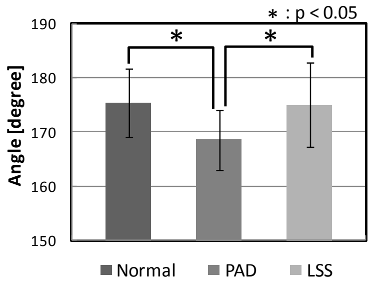



Fig. 12. Average angle of Angle III at the start of stance phase

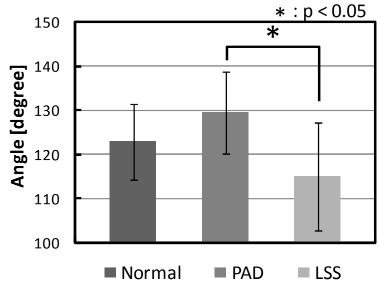



Fig. 13. Average angle of Angle IV

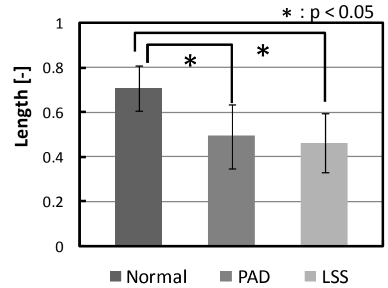



Fig. 14. Average length of hemi-foot step

shown in Fig. 6 (5)). Subsequently, knee joint bends a little bit for standing, and we get local minimum (corresponding postures are shown in Fig. 6 (6)-(8)). After that, to kick the belt to leave from the treadmill, the knee joint is extended and we get local maximum again (corresponding posture is shown in Fig. 6 (2)).

We focus on the bending angle of knee joint at the start of stance phase (corresponding posture is shown in Fig. 6 (5)). The angle for PAD patients was small comparing with it for normal healthy persons and it for LSS patients. The small angle for PAD patients is considered to be resulted from a gait strategy of a biophylactic response to crural muscle (musculus triceps surae and soleus muscles) which is most apt to go to ischemia due to walking load [1]. The two main mechanisms can be considered for it. One is that bending knee joint makes popliteal artery relaxed and then the diameter of the corresponding blood vessel increases. Therefore, we can deliver blood to crural muscle minimizing the loss of the blood flow at the knee joint in spite of the decrease of the blood flow at the upstream due to stenosis. The other one is the relaxation of crural muscle resulted from the flexion of knee joint. If crural muscle is relaxed, then external pressure to small blood vessel inside the muscle decreases, and then collapse and stenosis of blood vessel do not apt to cause. Then, we can decrease the effect of the decrease of blood flow due to arterial disease at the upstream. In case of LSS patients, the change of the bending angle was relatively small in swing phase, but the angle itself was not small especially at the start of stance phase.

Concerning this, we investigated the average values of the bending angle of knee joint at the start of stance phase. As it can be seen from Fig.9, there were little differences between the data just after the walking starts and the data just before the walking stops. Then, we focused on the data just after the walking starts. Fig. 12 shows the results. It shows that the bending angle for PAD patients is smaller than those for normal healthy persons and for LSS patients. We conducted statistical t test to the data. We got statistical significant differences between normal healthy persons and PAD patients and between LSS patients and PAD patients at the 5 % significant level. From these results, it can be said that the average bending angle of knee joint at the start of stance phase can be used as a factor for the disease differentiation.

### B. *Dorsiflexion angle of ankle joint.*

Here, we discuss the data of Angle IV corresponding to the dorsiflexion angle of ankle joint shown in Fig. 10. Spiked peak can be seen in Fig.10 (a). This spike peak means strong kicking at the moment when the leg leaves from the treadmill (corresponding posture is shown in Fig.6 (3)). After the leaving, the walking goes to swing phase. After that, the heel lands on the treadmill, flexing the ankle joint (stance phase starts), and then the ankle joint is extended to place the whole part of the foot on the floor (corresponding posture is shown in Fig. 6 (5)). After that, as the foot goes backward due to the motion of the treadmill, the ankle joint is flexed (corresponding postures are shown in Fig. 6 (6)-(8) and (1)). From Fig. 10, it can be seen that kicking's of LSS and PAD patients at the moment when the leg leaves from the treadmill were weaker than that of normal healthy persons. In addition, the average value of the dorsiflexion angle of ankle joint was small for LSS patients while it was large for PAD patients, comparing with that for normal healthy persons.

In case of PAD patients, if the amplitude of the dorsiflexion angle of ankle joint is large, the leg needs large amounts of blood, and ischemia could cause. Therefore, PAD patients do not move the ankle joint, and keep the amplitude small. On the other side, decreasing the dorsiflexion angle of ankle joint means extending calf muscle, and it leads to collapse the blood vessel of the calf. Then ischemia could cause and the PAD patients feel pain. To prevent this situation, they are considered to keep the dorsiflexion angle of ankle joint large.

LSS patients feel pain due to external press to spinal tissue by bone or soft tissue. Then, the pain can be relaxed if the patients bend forward [10]. Therefore, the feet of the LSS patients are apt to be placed backward comparing with the gravity center during the walking. It means the angle between the treadmill and the lower thigh is small. The angle corresponds to Angle IV (the dorsiflexion angle of ankle joint). Then its average value tends to be small.

Concerning this feature, we derived the average value of the dorsiflexion angle of ankle joint. As it can be seen from Fig.10, there was little difference between the data just after the walking starts and the data just before the walking stops. Then, we focused on the data just after the walking starts. Fig.

13 shows the results. From Fig. 13, it can be seen that the average angle for LSS patients was smaller than that for PAD patients. It coincides with the results shown in Fig.10. We conducted statistical t test and got statistical significant difference between LSS patients and PAD patients at the 5 % significant level. From this result, it can be said that the average value of the dorsiflexion angle of ankle joint can be used as a factor for the disease differentiation.

### *C. Hemi-foot step length*

Here, we discuss the data of hemi-foot step length shown in Fig. 11. The hemi-foot step lengths for LSS and PAD patients were smaller than that for normal healthy persons. The patients suffering from disorder in walking are apt to take the following walking strategy to prevent the pain at lower limbs and make the walking stable: to shorten the duration for putting the weight on the disorder leg. It is considered to be one of the reasons why the hemi-foot step length was small for PAD and LSS patients.

Concerning this feature, we derived the average value of the hemi-foot step length with respect to the data just after the walking starts since there was little difference between the data just after the walking starts and the data just before the walking stops. Fig. 14 shows the results. From Fig. 14, it can be seen that the average lengths for LSS and PAD patients are smaller than that for normal healthy persons, similarly to the results shown in Fig.11. We conducted statistical t test and got statistical significant differences between normal healthy persons and LSS patients and between normal healthy persons and PAD patients at the 5 % significant level. From these results, it can be said that the average value of the hemi-foot step length can be used as a factor for the disease differentiation, especially to differentiate normal healthy persons and patients.

### *D. Discussion*

From Fig.9, Fig.10, and Fig.11, it can be seen that there were little differences between the data just after the walking starts and the data just before the walking stops. It means that the symptom of the disorder appeared from the start of the walking. Namely, the walking motion data for 10 seconds just after the walking starts is enough to analyze and differentiate the diseases. We do not need the whole walking motion from the start to the time when the patients feel pain. It means the patients do not have to walk until they feel pain for the examination, and only have to walk for several seconds.

On the other side, we detected the three factors for disease differentiation from the 2 dimensional motion image analysis. Then, we can construct simple measuring system which even person (for example, medical doctor at small clinics) who does not have special professional knowledge can use.

## IV. Conclusion

This paper investigated the walking motions of normal healthy persons, PAD and LSS patients, aiming at the main problem identification of the patients suffering from intermittent claudication. The main results are as follows.

1. We showed that simple measuring system for walking is enough for the disease differentiation. We attached handmade LED markers on the 5 feature points of the subject and recorded the walking motion of the subject on the treadmill with commercial cheap camera. We only have to measure the motion of the limb where disorder causes from only one side, and then we need only one camera to measure the walking. Since the treadmill was used, walking motion can be measured in a small room which can be easily provided even in small hospitals and clinics. Even non-professional people such as medical doctors at small clinics can measure the walking.

2. We showed that: a) we can get enough information for the disease differentiation from 2 dimensional motion image (we do not need 3 dimensional information); b) Analyzing walking motion for 10 seconds just after the walking starts is enough for the disease differentiation, and then the patients can stop walking before feeling pain.

3. We derived 3 factors for the disease differentiation; average angle of Angle III (corresponding to bending angle of knee joint) at the start of stance phase, average angle of Angle IV (corresponding to dorsiflexion angle of ankle joint), and average hemi-foot step length. We will be able to construct the disease differentiation method/system by using 3 factors. It is our future work.

## References


[1] Y. Toribatake et al., “Classification and Differential Diagnosis of Intermittent Claudication,” *Spinal Osteomyelitis Journal*, vol. 21, no. 4, 2008, pp.333-340.

[2] Y. Toribatake et al., “The frequency and differential diagnosis of peripheral arterial occlusive disease in intermittent claudicants in orthopaedics,” *Orthopaedic surgery and traumatology*, vol. 45, no. 6, 2002, pp. 665-674.

[3] Y. Toribatake et al., “Vascular and neurogenic intermittent claudication,” *Cardioangiology*, vol. 56, no. 1, 2004, pp. 50-56.

[4] M. P. Murray, A. B. Drought, and R. C. Kory, “Walking patterns of normal men,” *the journal of bone and joint surgery*, vol. 46-A, no. 2, 1964, pp. 335-360.

[5] M. P. Murray, R. C. Kory, and S. B. Sepic, “Walking patterns of normal women,” *Archives of physical medicine & rehabilitation*, vol. 51, 1970, pp. 637-650.

[6] K. Yamanaka et al., “Localization of Walking or Running User with Wearable 3D Position Sensor,” *Technical report of IEICE. Multimedia and virtual environment*, vol. 106, no. 234, 2006, pp. 115-120.

[7] K. Kobara et al., “The Effect of Ankle Joint Rigidity in Plastic Ankle-Foot Ortho ses on the Ankle and Knee Joint Moments of Hemiplegics in the Walk-ing Stance Phase,” *Kawasaki medical welfare journal*, vol. 16, no. 2, 2006, pp. 299-304.

[8] A. Tokura, “Kinesiologic and Kinematic Analysis of Walking Pattern on Osteoarthritis of the Hip,” *J. Jap. Orthop. Ass.*, vol. 48, no. 1, 1974, pp. 1-11.

[9] A. Tanabe et al., “Treadmill gaint analysis of pre/post operation in total hip replacement,” *Congress of Japanese Private Medical College Physical Therapy*, vol. 22, no. 1, 2005, pp. 17-20.

[10] K. Takahashi et. al., ‘‘Changes in epidural pressure during walking in patients with lumbar spinal stenosis,’’ *Spine*, vol.20, 1995, pp.2746-2749.

[11] Bruce D.Lucas, Takeo Kanade, “An lteretive Image Reg-istration Technique with an Application to Stereo Vision,” *Proc. 7th Int. Conf. on Artificial Intelligence (IJCAI)*, 1981, pp.674-679.