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classification of paper : Original Paper

paper title : Volume Measurement of the Leg by Using Kinect Fusion for Quantitative Evaluation of Edema

author names : Kaoru KIYOMITSU⁽¹⁾, Akihiro KAKINUMA⁽²⁾, Hiroshi TAKAHASHI⁽²⁾, Naohiro KAMIJO⁽²⁾, Keiko OGAWA⁽³⁾, Norimichi TSUMURA⁽¹⁾

affiliation :

(1) Graduate School of Advanced Integration Science, Chiba University

(2) Ricoh Company, Ltd.

(3) Department of Japanese-Traditional (Kampo) Medicine, Kanazawa University Hospital

address : 1-33, Yayoi-cho, Inage-ku, Chiba-shi, Chiba, 263-8522 Japan

E-mail address : kiyomitsu@chiba-u.jp

(2) Abstract

In this paper, we propose to evaluate the edema of a leg by volume measurement using Microsoft Kinect. The volume is calculated from a measured point cloud by our improved voxelization technique. Additionally, the depth camera of Microsoft Kinect is feasible for use in home care systems due to its very low cost compared with other depth cameras. In an experiment, we measured the leg volumes of three healthy subjects in the morning and evening for three days. For each subject, the mean volume values were obtained from five measured values. The increase of volume was confirmed in all experiments from morning to evening. These experimental results meet the physiological expectation. Because the changes in leg volumes are greater for a patient with serious edema than for a healthy person, we conclude that the proposed system can appropriately evaluate leg edema.

(3) Keywords

edema, health monitoring, Kinect, point cloud, volume measurement

(4) Main text

1. Introduction

Edema is swelling of the leg, hand, or face due to the accumulation of body serum. Many healthy people have minor edema. However, some patients who are treated for cancer or other illnesses have serious edema. To relieve edema, continual long-term treatments such as massage or exercise are needed¹⁻²⁾. Simultaneously, quantitative evaluation of edema can help motivate patients by preventing the boredom of extra treatments.

Volume measurement of a limb is one of the practical methods for quantitative evaluation of edema³⁾. The volume of a limb increases or decreases according to the volume change of body serum. In other words, an increase or decrease of volume indicates whether the edema is getting worse or better. Currently, hospitals use a measuring tape to measure the circumference of a patient's limb instead of its volume value³⁻⁵⁾. Although this method is easy, it has poor repeatability and accuracy.

In recent years, methods using a depth camera have been proposed to obtain the leg volume^{6,7)}. The first step of these methods is acquisition of a 3D model of a subject's leg. A 3D model for the entire leg can be obtained by two types of imaging procedures. One is performed by moving a single camera around the subject's leg. The other is performed by setting several cameras around the subject's leg. The next step is a calculation of the volume by computations on the 3D model. Some previous methods have used a depth camera for the volume measurement. However, it is not feasible to use a depth camera as a home care system because most depth cameras are too expensive.

In this paper, we propose to evaluate the edema of a leg by using Microsoft Kinect for the volume measurement. Kinect, shown in Fig. 1, is an RGB-D system that can obtain a depth map as well as an RGB image⁸⁾. Kinect is already well known throughout the world as a game controller. "Kinect for Windows SDK" contains Kinect Fusion^{9,10)}, which is an application to easily obtain a 3D model.

The purpose of our study is the quantitative evaluation of edema. Therefore, it is necessary to precisely measure the amount of change of the volume. We constructed a reproducible measurement system whose output value has less dispersion in repetitive measurements. In this paper, we only measured the volume of a leg because the leg shows a higher degree of edema compared to the rest of the body.

In Section 2, we describe our proposed method to measure the volume of a leg. In Section 3, we describe the experiments and results of this study. In Section 4, we present the conclusion of our study.

2. Proposed Method

In this study, we measure the volume of the leg by using Kinect. First, we scan the leg with the Kinect Fusion technique, and then we obtain the point cloud of the leg in real time. Second, the point cloud is processed to remove unnecessary parts. To decide the measurement range, we set the coordinate axis along the leg length. Finally, the volume value is obtained by voxelization.

2.1 Acquisition of a Point Cloud

We use Kinect Fusion^{9,10)} for acquisition of the point cloud of the leg. Kinect Fusion is one of the applications contained in Kinect for Windows SDK. We can obtain a point cloud in real time by scanning around the leg with a Kinect sensor, which used as a hand-held depth camera. Figure 2 shows a screenshot of the recording procedure by Kinect Fusion. We can move the Kinect sensor while looking at the reconstructed point cloud on the monitor in real time, so that it is possible to scan the leg while checking for errors, such as a missing surface or a hole of the point cloud.

2.2 Removal of Unnecessary Parts

The point cloud obtained by Kinect Fusion includes not only the leg but also other parts, such as a chair and the floor. We need to remove these unnecessary parts. First, we remove the points except the leg and the floor. For this procedure, we use MeshLab¹¹⁾, which is free software for editing a 3D model. With this software, we can remove, translate, rotate, and fill a hole of a point cloud. Figure 3 shows the result of removal of a chair by MeshLab. After this procedure, the floor still remains. It is difficult to remove floor parts from a point cloud because the arch of the foot is attached to the floor. Therefore, we remove the floor parts automatically, as shown in Fig. 4, by a plane model segmentation algorithm. Simultaneously, we translate and rotate the point cloud to reset its coordinates by setting the XZ plane along the floor. Thus, the Y-axis becomes the length of the leg. This is the preprocessing step for the following procedure, which is setting the measurement range.

2.3 Setting the Stable Range of the Measurement

We decide the stable range of the measurement according to the height of the leg. The purpose of our study is the measurement of the change of volume; therefore, it is important to set a stable range of the measurement. In this method, we extract the intended point cloud by masking along the height of the leg. As stated in the previous subsection, the direction of the leg length corresponds to the Y-axis due to preprocessing. We carry out masking with the Y-coordinate to set the range of the measurement.

2.4 Calculation of the Volume

The point cloud obtained by Kinect Fusion has errors such as a hole or a missing surface. These errors tend to occur on the back side of the leg. Additionally, undesired points which should be treated as noise may easily appear on the inside of the surface. For this reason, it is necessary to consider these errors. Although some techniques for calculation of volume value are proposed, most of these methods are disabled by holes or noise. In this study, we use a simple and stable method to correct these errors. Our method is modified method based on the previous methods proposed by Garcia *et al.*¹²⁾ and Saito *et al.*¹³⁾.

Here, we discuss the method proposed by Garcia *et al.*¹²⁾. They proposed the method of voxelization. First, they conducted voxelization on the surface of the point cloud. As shown in Fig. 5, each point in the point cloud is assigned to one voxel. Second, we extract the voxels that contain points. In Fig. 5, the voxels that contain points are white, and the other voxels are black. The following procedure is implemented on planes sliced along the X-axis, Y-axis, and Z-axis. Figure 6 shows an example of the sliced planes along the Z-axis. The planes thus are each XY planes. Third, the surface of the connected voxels is constructed by interpolation between each white voxel. As shown in Fig. 7, each white voxel is chained to its nearest voxels, and, voxelization of the surface is complete. The next procedure is voxelization of the volume; voxelization is performed row by row of the voxels. In each row, the black voxels between two white voxels become white. Figure 8 shows the result of voxelization of the voxels on the surface of Fig. 7. If the row lies on the concave and convex curve line such as the toe, it may have more than three white voxels. In such cases, the black voxels between the first white voxel and the second white voxel become white, then the black voxels between the third white voxel and the fourth white voxel become white, and so on. This procedure assumes that every row has an even number of white voxels. However, in the case of the rows having an odd number of white voxels, the black voxels between the last white voxel and the rightmost voxel become white. This voxelization is implemented on all rows in each sliced plane.

Next, we discuss the method proposed by Saito *et al.*¹³⁾. Saito's method is based on Garcia's method. Saito's method of voxelization for the surface is the same as Garcia's, but voxelization of the volume is implemented by labeling the voxels. Figure 9 shows an example of voxelization of the volume. The volume of the point cloud is obtained by counting the number of white voxels.

Finally, we propose the improved voxelization technique, which is effective for the point cloud obtained by Kinect Fusion. The previous two methods assume that all of the points are placed on the surface of the point cloud; in other words, no points are inside the surface. However, the point cloud obtained by Kinect Fusion tends to have interior points. Figure 10 shows an example of the surface voxelization in the case that some

interior points are present. In this case, undesired lines and/or untreated holes may easily appear. It is noted that the surface voxelization is implemented on a sliced plane along only the Y-axis, whose direction is the same direction as the leg length.

Volume voxelization is also affected by the interior points. Figure 11(a) shows the procedure of Garcia's volume voxelization on the surface in Fig. 10. Gray voxels present the volume voxelized voxels which turn from black to white. Figure 11(b) shows the result of this volume voxelization. In this case, the rows having an odd number of white voxels cause an error. For this reason, our method detects the last white voxel in the scanning and keeps voxels as black after the last white voxel is detected in the second scanning for each row. Figure 11(c) shows the result of our volume voxelization of Fig. 10. Our improvement prevents an error due to interior points. It should again be noted that the volume voxelization is implemented on a sliced plane along only the Y-axis.

The next step is filling any hole of the point cloud. We propose a method based on Saito's method. Saito's method implements labeling on the assumption that a blank region that is not a leg region includes the voxels on the upper-left corner and the upper-right corner of the sliced plane, namely, the leftmost voxel and the rightmost voxel of the top row.

Sometimes the point cloud obtained by Kinect Fusion has neither an upper-left corner nor an upper-right corner. Therefore, we add an outer frame to the sliced plane in advance, as shown in the left figure of Fig. 12. Due to the outer frame, a blank region can constantly include an upper-left corner and an upper-right corner. Then, we can turn black voxels that are not in the blank region into white voxels. As mentioned above, the surface and volume voxelizations are implemented on a sliced plane along only the Y-axis. In contrast, the labeling method is implemented on a sliced plane along the Y-, X-, and Z-axes. The right figure of Fig. 12 is the result of our proposed voxelization. The volume value can be calculated by the voxel number and the size of the unit voxel.

3. Experiment

In this study, first we verified the accuracy of our method. Second, we measured the change of the volume of healthy subjects' legs from morning to evening.

3.1 Measurement with a Leg Model

We first measured the volume of a leg model that is not affected by motion of the leg. This motion could influence the accuracy, and so we use motionless model to verify the accuracy. Figure 13 shows a picture of the leg model. The operator held the Kinect sensor in the hand and scanned three times around the model leg. The distance between the Kinect sensor and the leg was kept at approximately 35 cm. This procedure was repeated five times, so that we obtained five point clouds for each measurement and then we

calculated the volume values. In our study, the unit voxel was determined to be a cube with a side of 1 mm.

We measured the volumes of the five point clouds within the range from 0 cm to 30 cm to verify the accuracy. We used the coefficient of variation as a parameter of the dispersion of the measured volume. The coefficient of variation is calculated as the ratio between the standard deviation and the mean value of the volumes. The smaller the variation of coefficients becomes, the better the accuracy. The coefficient of variation within the range from 0 cm to 30 cm was 1.04%.

Next, the range of the measurement was divided into four regions. Figure 14 shows the coefficients of variation of the four parts. The range from 0 cm to 5 cm has the largest dispersion due to occlusion caused by the lumpy sole of the model's foot. Therefore, we recalculated the coefficient of variation within the range from 5 cm to 30 cm, excluding the range from 0 cm to 5 cm. The result of the recalculation was 0.70%, which is a decrease compared with the result from 0 cm to 30 cm. We found that we can measure the volume of the leg stably by removing the region of the foot in the case of the leg model.

3.2 Measurement with a Human Leg

We performed an experiment for the human leg by the same procedure used for the leg model. The subjects were two males and one female. Every subject was a healthy adult. Each subject sat on a chair with a bare right leg, which was posed to be a right angle with respect to the floor. The experimental condition is shown in Fig. 3. In this experiment, we measured the volume of the leg in the morning (AM) and evening (PM) for three days. In each measurement, the mean value and the coefficient of variation were obtained from the five measured values. We divided the leg into four regions, as was done for the leg model discussed in the previous section. In this section, the boundaries of the regions were (A) ankle, (B) boundary between ankle and calf, (C) thickest point in the calf, and (D) point below the knee, as shown in Table 1. Figure 15 shows the result of subject A for the four regions: 0–(A), (A)–(B), (B)–(C), and (C)–(D). This result shows that region (A)–(B), namely, the region of his ankle, tends to have the largest dispersion due to an occlusion caused by the complex shape of the subject's ankle bone. The same tendencies were seen in the results of the other two subjects. Figure 16 shows the comparison between the result with an ankle and the result without it for all three subjects. Blue bars show the coefficient of variation with the ankle and red bars show the coefficient of variation without the ankle. Graph (a), (b) and (c) show the results of Sub. A, Sub. B and Sub. C, respectively. This graph shows that the coefficients of variation can be reduced by removing the ankle from the measurements. The coefficients of variation of the volumes of human legs were within the range of 0.5%–2.5%. The coefficients of variation reflected the influence of leg movement during scanning. The

difference of the region removed was the difference of shape between the leg model and the human model.

3.3 Measurement of the Volume Change for Healthy Subjects' Legs

In this experiment, we measured the volume of the leg for the three healthy subjects in the morning (AM) and evening (PM) for three days. Figure 17 shows the result of the measurement. Red lines show the mean value of five measured volume values which are shown by five blue points in morning and evening. Graph (a), (b) and (c) show the results of Sub. A, Sub. B and Sub. C, respectively. Each volume was calculated from the total sum of the three parts of the leg, except for the region (A)–(B) in Table 1. During this experiment, every subject was carrying out office work. It is known that the edema occurs on the human's leg when the subjects are doing office work; in other words, they are sitting in the chair for many hours. The edema causes the increase of the volume of the leg because the body serum is accumulated in the leg. Therefore we had expectation for office workers that the volume of the leg is increased in the evening compared in the morning. It is noted that the increased volume was confirmed in all experiments from morning to evening. Therefore, we can conclude that our experimental results meet the expectation for office workers. Our system is practical for measuring leg edema because the changes in leg volumes are greater for a patient with serious edema than for a healthy person.

4. Conclusion

In this paper, we proposed a method of volume measurement using Microsoft Kinect for the evaluation of a leg edema. We obtained a point cloud of the leg by the Kinect Fusion technique and calculated its volume. We measured the volume of the leg of three healthy subjects from morning to evening for three days. The coefficients of variation of the volumes of the human legs were within the range of 0.5%–2.5%. Our experimental results meet the expectations of their life style. Our future work is measurement of a leg of a patient with edema. Additionally, we aim to measure a leg of a patient lying with a bended knee. This technique will make it possible to deal with bedridden people.

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Caption of figures

Fig.1 Microsoft Kinect

Fig.2 Screenshot of recording by Kinect Fusion

Fig.3 Removal of unnecessary parts by MeshLab

Fig.4 Removal of the floor by the plane model segmentation algorithm

Fig.5 Voxelization of the surface of the point cloud. White voxels present the surface of the point cloud, and black voxels present the blank region.

Fig.6 Sliced planes along the Z-axis

Fig.7 Voxelization of the surface proposed by Garcia¹²⁾

Fig.8 Voxelization of the volume proposed by Garcia¹²⁾

Fig.9 Voxelization of the volume proposed by Saito¹³⁾

Fig.10 Voxelization of the surface of the point cloud that has interior points

Fig.11 Volume voxelization of the point cloud that has interior points. (a) shows the procedure of Garcia's method¹²⁾. Gray voxels present the volume voxelized voxels which turn from black to white. (b) shows the result of Garcia's method¹²⁾. (c) shows the result of our method.

Fig.12 Volume voxelization of our method

Fig.13 Leg model with the scale of the height from the floor

Fig.14 Coefficients of variation of five measured values in four measured regions of the leg model

Fig.15 Coefficients of variation of the five volume values in four parts of subject A's leg. This experiments were conducted six times.

Fig.16 Coefficients of variation of the five measured values of the leg of subjects. Blue bars show the coefficient of variation with the ankle and red bars show the coefficient of variation without the ankle. Graph (a), (b) and (c) show the results of Sub. A, Sub. B and Sub. C, respectively.

Fig.17 Results of the experiments for the three healthy subjects' legs. Red lines show the mean value of five measured volume values which are shown by five blue points in morning and evening. Graph (a), (b) and (c) show the results of Sub. A, Sub. B and Sub. C, respectively.

Tables

Table. 1 Heights of four selected points from the floor (cm)

	Sub. A (Male)	Sub. B (Male)	Sub. C (Female)
(A) ankle	8	10	8
(B) boundary between ankle and calf	20	21	20
(C) thickest point in calf	33	34	27
(D) point below knee	37	40	35

Figures



Fig. 1

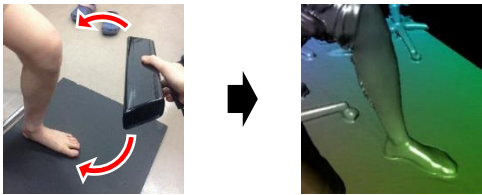


Fig. 2

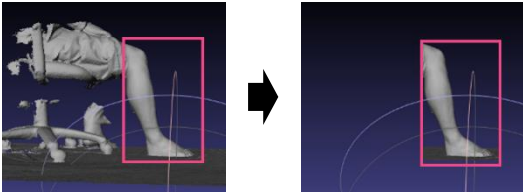


Fig. 3

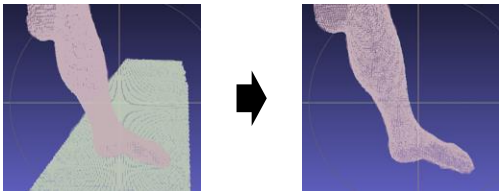


Fig. 4

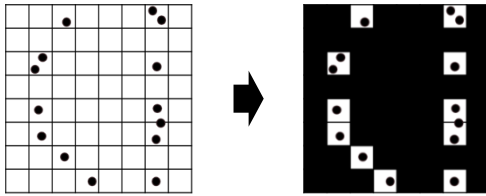


Fig. 5

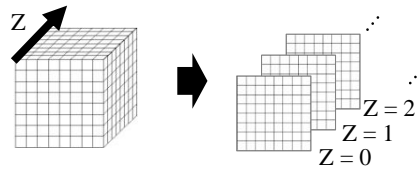


Fig. 6

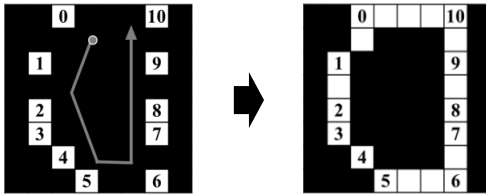


Fig. 7

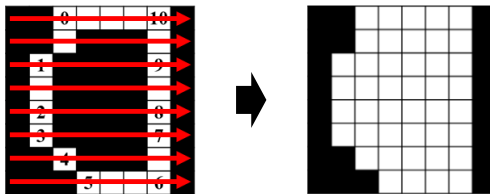


Fig. 8

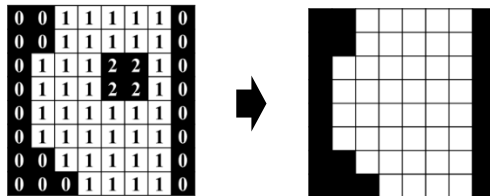


Fig. 9

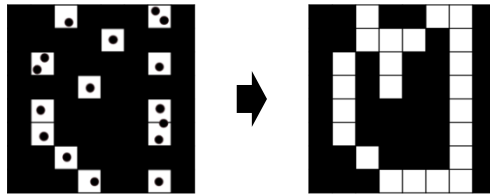


Fig. 10

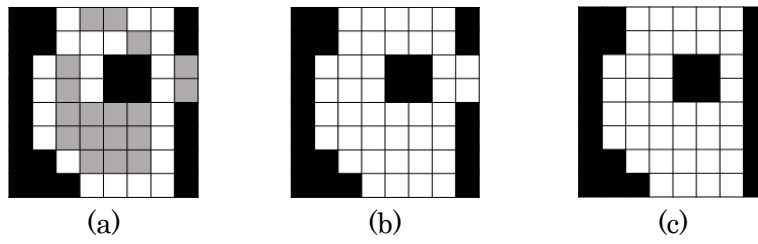


Fig. 11

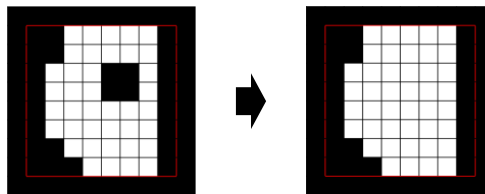


Fig. 12



Fig. 13

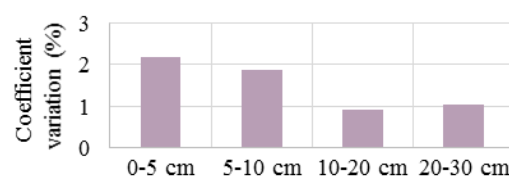


Fig. 14

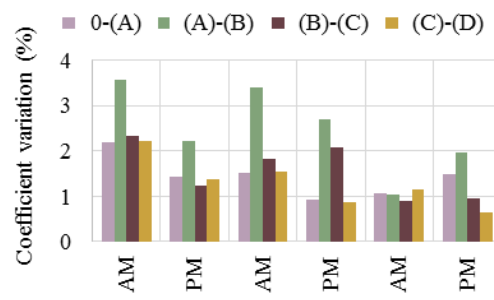
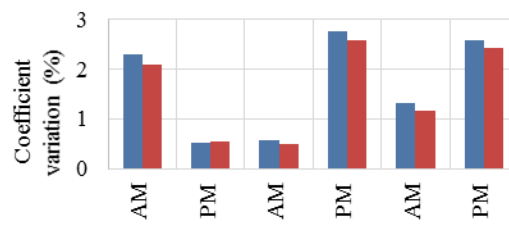


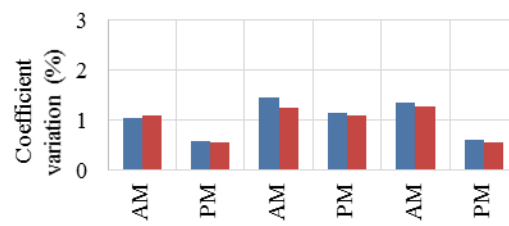
Fig. 15



(a)

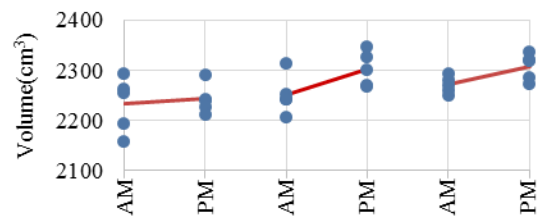


(b)

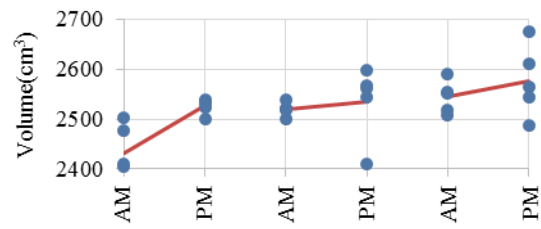


(c)

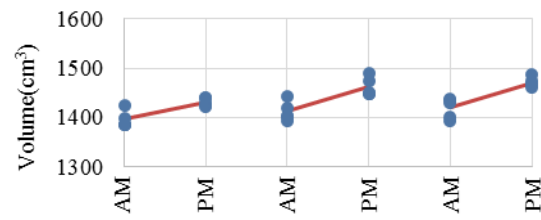
Fig. 16



(a)



(b)



(c)

Fig. 17