Development of Three-Dimensional Motion Measuring Device for the Human Ankle Joint by Using Parallel Link Mechanism

Teru Yonezawa, Takayuki Onodera,
Ming Ding, Hiroshi Mizoguchi, Hiroshi Takemura, Takeki Ogitsu.

Abstract— **This paper presents a novel ankle motion measuring device that can measure three-dimensional motions without a motion capture system (MCS). We adapted a parallel link mechanism for the device using six wire-type displacement sensors to measure the ankle joint motions in six degrees of freedom (six-DOF). We define the motions of a foot plate which is attached to a foot sole as ankle joint motions. A posture of the foot plate, i.e., the three-dimensional position (x, y, z) and rotation angle (θ, φ, ψ), is numerically calculated by solving the forward kinematics of the developed device. We conducted performance verification experiments of the developed device by comparing these results with those of the MCS. The experimental results show that the maximum root mean square error of the three-dimensional position and rotation angle measured by the developed device are 2.6 mm and 1.5°, respectively. This measuring performance of the developed device indicates that the ankle motion measuring device is accurate and valid. Moreover, this device enables physical therapists to easily measure ankle motions with an accuracy as high as that of an MCS.**

I. INTRODUCTION

Quantitatively measuring and analyzing human motions is very important in various fields, including product design, sports, medicine, and rehabilitation. In particular, in the field of rehabilitation medical treatment, measuring human motions with high accuracy is required to evaluate the degree of physical disability and effect of rehabilitation. However, at nearly all clinical sites, high-accuracy measurements of human motions have not been clinically performed.

Range of motion (ROM) is one of the most widely used parameters to evaluate the effect of rehabilitation or degree of physical disability [1]. In general, ROM is measured by a physical therapist (PT) using a goniometer: an instrument to measure the joint angle, as shown in Fig. 1. However, the measured values by a goniometer tend to contain therapist's subjectivity and have large dispersions because therapists decide the reference line by eye-measurements and read the scale of the goniometer i.e., the output is not digital [2]. Moreover, measuring the ROM of a joint with a high-degree of freedom (DOF), e.g., the ankle joint, is not easy because therapists measure the ROM from various directions while supporting the patient's body. In the rehabilitation field, the ease of ROM measurement and measured values lacking objectivity are serious issues.

In this study, we focus on the ankle joint, which is one of the most complex joints of human body. As shown in Fig. 2, the ankle joint is a compound joint consisting of four bones (tibia, fibula, talus, and calcaneus), and its motions are combination motions by mainly the talocrural and subtalar joints [3]. Generally, the ankle joint is regarded as a three-DOF joint that moves in three rotational directions (dorsiflexion and planter flexion, inversion and eversion, and adduction and abduction), as shown in Fig. 3. However, because the rotation axes move in three-dimensions, the ankle joint moves in six-DOF [4]. The limitation of the ankle joint motions leads to the inability to perform daily living activities. Even if the restriction of the ankle joint is minimal, the effect in the walking ability, such as ascending and descending stairs, and as well as standing and squatting become a serious problem. Therefore, high-accuracy motion measurements of the ankle joint are more important than those of other joints.

There are measurement methods for the ankle joint motions using X-ray equipment [5] or a motion capture system (MCS) [6], [7]. The measurement using X-ray equipment can measure the ankle joint ROM with high-accuracy because therapists can directly see the positional relation of the bones by the X-ray photograph; however, this method cannot sufficiently measure continuous changes of the ankle joint. Moreover, because of the projection images, X-ray equipment can only measure two-dimensional motions. The measurement using MCS can accurately measure three-dimensional motions. However, this method requires a complicated preparation, which includes setting cameras and markers or performing calibrations. In both of these methods, the scale of the devices is large. Therefore, the measurement locations are limited because of the special environment required for the measurement.

In recent years, wearable devices for the human ankle joint have been developed [8], [9]; however, most of devices have been developed for ankle joint rehabilitation not for measuring ankle motions. It is possible to measure ankle motions from controlled amount of the actuator of devices; however, the DOF of most devices is one or two. Therefore, such devices cannot measure the ankle motion in six-DOF.

This paper presents a novel ankle motion measuring device that can measure three-dimensional motions of the ankle joint based on the parallel link mechanism using wire-type displacement sensors. The advantage of the developed device is that it can easily measure the ankle joint motions in six-DOF without an MCS.

This paper is organized as follows. The following section explains a measuring method for the ankle joint motion by solving the inverse kinematics of the parallel link mechanism. In Section 3, the mechanism of the developed device is presented. Then, the efficacy of the developed device is experimentally demonstrated in Section 4, and the conclusions are summarized in the last section.

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Teru Yonezawa, Takayuki Onodera, Hiroshi Mizoguchi, Hiroshi Takemura, and Takeki Ogitsu are with Tokyo University of Science, 2641, Yamazaki, Noda-shi, Chiba, Japan (corresponding author to provide phone: 04-7124-1501 (3931); fax: 04-7123-9814; e-mail: 7514652@ ed.tus.ac.jp).

Ming Ding is with Nagoya University, Furocho, Nagoya Chikusa-ku, Aichi, Japan.

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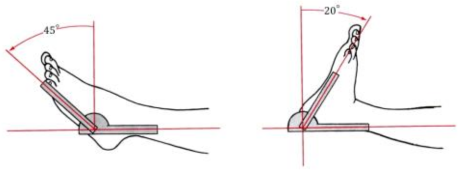
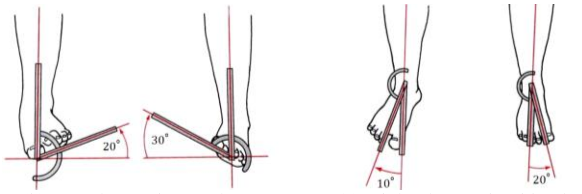


(a) Planter flexion and Dorsiflexion



(b) Eversion and Inversion (c) Abduction and Adduction

Figure 1. Conventional ROM measurement method of the ankle joint.

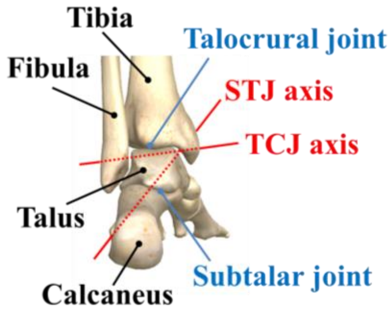


Figure 2. Structure of the ankle joint.

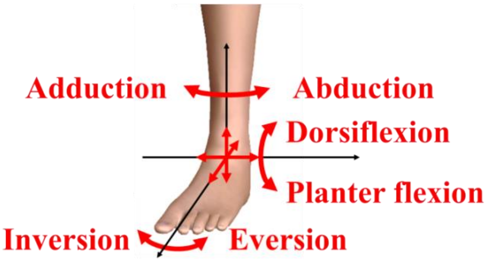


Figure 3. Motions of the human foot.

II. METHOD OF 3D MOTION MEASURING

This section describes the numerical method for calculating the foot posture. Fig. 4 shows the geometric model of a parallel link mechanism called Stewart Platform [10] that we adopted for the device. The moving plate (red area) and the base plate (blue area) are connected by six links. $\boldsymbol{\Sigma_B}$ and $\boldsymbol{\Sigma_M}$ are the coordinate systems of the base plate and the moving plate, and $\boldsymbol{O_B}$ and $\boldsymbol{O_M}$ are origin of $\boldsymbol{\Sigma_B}$ and $\boldsymbol{\Sigma_M}$, respectively. In $\boldsymbol{\Sigma_B}$, the position of $\boldsymbol{O_M}$ is $\boldsymbol{p}$, the position where a link is connected to the base plate is $\boldsymbol{b_i}$, and the position where a link is connected to the moving plate is $\boldsymbol{w_i}$. In $\boldsymbol{\Sigma_M}$, the position where a link is connected to the moving plate is $\boldsymbol{m_i}$. In this study, we define the motions of the foot plate (moving plate), which is attached to a foot sole, as the ankle joint motions. Analytically calculating the posture of the foot plate from the length of each link (forward kinematics) has not been done in this type of parallel link mechanism. Conversely, analytically calculating the length of each link from the foot plate posture (inverse kinematics) is available [11]. In this study, we numerically solved the forward kinematics using the inverse kinematics and calculated the posture of the foot plate $\boldsymbol{P} = [\boldsymbol{p}\ \boldsymbol{r}]^T$, where $\boldsymbol{p}$ is the three-dimensional position ($\boldsymbol{p} = [x\ y\ z]^T$) and $\boldsymbol{r}$ is the rotation angle ($\boldsymbol{r} = [\theta\ \varphi\ \psi]^T$).

A. *Inverse kinematics*

As shown in Fig. 4, $\boldsymbol{w_i}$ can be expressed as

$$\boldsymbol{w_i} = \boldsymbol{p} + \boldsymbol{R}_{(r)} \cdot \boldsymbol{m_i}\ , \tag{1}$$

where $\boldsymbol{R_{(r)}}$ is a rotation matrix that rotates $\boldsymbol{\Sigma_M}$ from $\boldsymbol{\Sigma_B}$. From (1), the length of a link l_i is calculated as

$$l_i = \|\boldsymbol{p} + \boldsymbol{R}_{(r)} \cdot \boldsymbol{m_i} - \boldsymbol{b_i}\|\ . \tag{2}$$

From the above, when $\boldsymbol{P}$ is known, l_i can be easily calculated.

B. *Forward kinematics*

When the length of each link is defined as $\boldsymbol{L} = [l_1\ l_2\ l_3\ l_4\ l_5\ l_6]^T$, the relation between $\boldsymbol{P}$ and $\boldsymbol{L}$ can be determined as

$$\dot{\boldsymbol{L}} = \boldsymbol{J}\dot{\boldsymbol{P}}\ , \tag{3}$$

where $\boldsymbol{J}$ is the Jacobi matrix, which is expressed as

$$\boldsymbol{J} = \begin{bmatrix} \boldsymbol{d_1^T} & (\boldsymbol{m_1} \times \boldsymbol{d_1})^{\boldsymbol{T}} \\ \boldsymbol{d_2^T} & (\boldsymbol{m_2} \times \boldsymbol{d_2})^{\boldsymbol{T}} \\ \boldsymbol{d_3^T} & (\boldsymbol{m_3} \times \boldsymbol{d_3})^{\boldsymbol{T}} \\ \boldsymbol{d_4^T} & (\boldsymbol{m_4} \times \boldsymbol{d_4})^{\boldsymbol{T}} \\ \boldsymbol{d_5^T} & (\boldsymbol{m_5} \times \boldsymbol{d_5})^{\boldsymbol{T}} \\ \boldsymbol{d_6^T} & (\boldsymbol{m_6} \times \boldsymbol{d_6})^{\boldsymbol{T}} \end{bmatrix}, \tag{4}$$

where $\boldsymbol{d_i}$ (i=1,…,6) is direction vector of the link, defined as

$$\boldsymbol{d_i} = \frac{\boldsymbol{w_i} - \boldsymbol{b_i}}{\|\boldsymbol{w_i} - \boldsymbol{b_i}\|}\ . \tag{5}$$

When the inverse matrix of $\boldsymbol{J}$ exists, (3) can be converted into (7).

$$\dot{\boldsymbol{P}} = \boldsymbol{J}^{-1}\dot{\boldsymbol{L}}\ , \tag{6}$$

$$\boldsymbol{P_{n+1}} = \boldsymbol{P_n} + \boldsymbol{J_n^{-1}}(\boldsymbol{L_{n+1}} - \boldsymbol{L_n})\ . \tag{7}$$

$\boldsymbol{L_{n+1}}$ is a measured value. From the initial posture $\boldsymbol{P_0}$, which is set to an optional position, $\boldsymbol{J_0^{-1}}$ and $\boldsymbol{L_0}$ are calculated, and $\boldsymbol{P_1}$ is determined. Furthermore, $\boldsymbol{P_2}$ is determined from $\boldsymbol{P_1}$. $\boldsymbol{P_n}$ is updated such that $\boldsymbol{L_n}$ approaches $\boldsymbol{L_{n+1}}$. When $(\boldsymbol{L_{n+1}} - \boldsymbol{L_n}) \approx 0$, $\boldsymbol{P_{n+1}}$ is determined to be $\boldsymbol{P}$. By this convergent calculation, forward kinematics of the developed device can be solved.

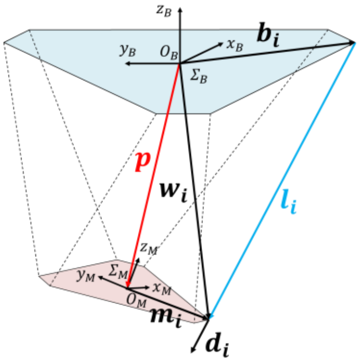


Figure 4. Geometric model of the parallel link mechanism.

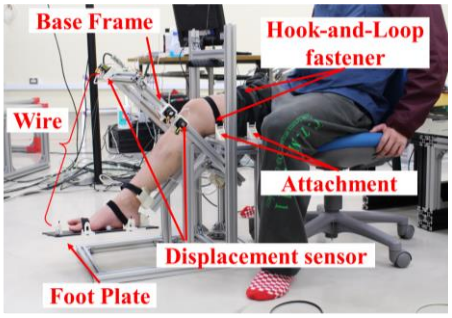


Figure 5. Ankle ROM measuring device.

III. DEVELOPMENT OF ANKLE ROM MEASURING DEVICE

Fig. 5 shows the developed ankle motion measuring device using a parallel link mechanism. Six wire-type displacement sensors (potentiometer) are mounted on the base frame. Each wire end is connected to the foot plate. In this study, we assume that the motions of the foot plate are the motions of the ankle joint. The subject's foot and leg are fixed by Hook-and-Loop fasteners and attachments, which are made by a 3D printer, as shown in Fig. 5. By the fixing subject's hip and knee joints, the device enables us to measure only the ankle joint motions.

IV. PERFORMANCE VERIFICATION EXPERIMENT

This section discusses the measuring accuracy of the developed device. $\boldsymbol{P_D}$ is the posture of the foot plate, which is measured by our developed device, and $\boldsymbol{P_M}$ is the posture of the foot plate, which is measured by MCS (Opti Track S250e, Natural Point, Inc.). We defined $\boldsymbol{P_M}$ as the true value and evaluated the measuring performance of the developed device by comparing $\boldsymbol{P_D}$ with $\boldsymbol{P_M}$.

Figs.6 and 7 show the coordinate system of the base frame and foot plate, respectively. The coordinate system of MCS was matched with the coordinate system of the base frame using the calibration plate, i.e., the black L-shaped plate in Fig. 6. Markers for the MCS were set on the foot plate, as shown in Fig. 7. We used the measured value of marker *c* as the original point of the three-dimensional position of the foot plate. The rotation angle of the foot plate was calculated using a rotation matrix, which rotated the coordinate system of Foot Plate. Eleven MCS cameras are used to measuring the foot plate motions, as shown in Fig. 8. The sampling frequency of the developed device and MCS were set 100 and 250 Hz, respectively. We conducted two experiments: static and dynamic. .

Static experiment: measurement of the posture of the foot plate, which is fixed for 3 s by the MCS and developed device.

Dynamic experiment: measurement of the posture of the foot plate which, is moved for 10 s by MCS and developed device.

A. Static experiment

In this experiment, we measured eight postures of the foot plate, which was optionally fixed. We calculated the maximum error and root mean square error (RMSE) from the errors of eight postures. Table I lists the maximum error and RMSE of the origin position and rotation angle, which were calculated from $\boldsymbol{P_D}$ and $\boldsymbol{P_M}$. The maximum error for the origin position and rotation angle is 5.1 mm and 1.0 °, respectively. Meanwhile, the maximum RMSE for the origin position and rotation angle is 2.7 mm and 0.5 °, respectively.

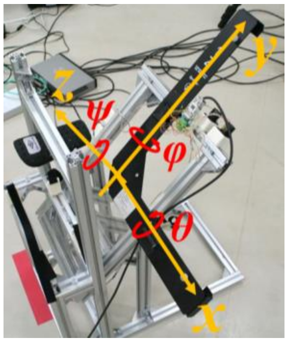


Figure 6. Coordinate system of the base frame.

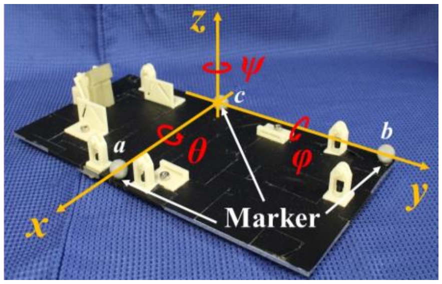


Figure 7. Coordinate system of the foot plate.

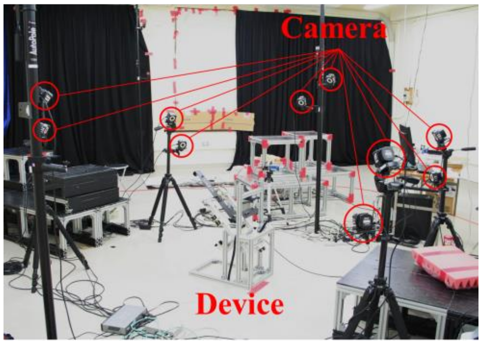


Figure 8. MCS camera setup.

TABLE I.
THE MAXIMUM ERROR AND RMSE OF THE STATIC EXPERIMENT

	Maximum error	RMSE
x [mm]	4.0	2.4
y [mm]	5.1	2.7
z [mm]	2.2	1.3
θ [deg]	0.5	0.4
φ [deg]	0.7	0.4
ψ [deg]	1.0	0.5

B. Dynamic experiment

In this experiment, we attached the foot plate to a subject's foot and measured the rotational motions of the foot plate four times. We calculated the maximum error and RMSE from errors at each sampling time. E.g., the error of the *x* direction $e_{x,i}$ is defined as

$$e_{x,i} = P_{M_{x,i}} - P_{D_{x,i}}, \tag{8}$$

where i is a number of samples (i =1, 2, 3, …, n), and $P_{M_{x,i}}$ and $P_{D_{x,i}}$ are the component x of $\boldsymbol{P_M}$ and $\boldsymbol{P_D}$, respectively (In this experiment, n=500).

The RMSE of the x direction RMSE_x is expressed as

$$\mathrm{RMSE}_x = \sqrt{\frac{\sum_{i=1}^{n}\left(e_{x,i}\right)^2}{n}}. \tag{9}$$

RMSEs of the other positions (y, z) and rotation angles (θ, φ, ψ) are also calculated in the same method as (8) and (9).

An example of the results is shown in Fig. 9 (Red line: $\boldsymbol{P_M}$; Blue line: $\boldsymbol{P_D}$). Fig. 9(a) shows the relationship between time and the position of the foot plate. Fig. 9(b) shows the relationship between time and the rotation angle of the foot plate. Notice that most of $\boldsymbol{P_D}$ overlaps with $\boldsymbol{P_M}$. This indicates that our developed device can measure the dynamic change of the posture of the foot plate. Table II lists the maximum error and RMSE of the origin position and rotation angle, which were calculated from the error of each sampling time. The maximum error of the origin position and rotation angle is 10.6 mm and 6.3 °, respectively. Meanwhile, the maximum RMSE of the origin position and rotation angle is 2.6 mm and 1.5 °, respectively.

V. CONCLUSION

A novel three-dimensional motion measuring device for the human ankle joint using a parallel link mechanism has been developed, and its performance has been evaluated. Using six displacement sensors, the developed device can easily and accurately measure six-DOF motions of the ankle joint without an MCS. The experimental results show that the maximum RMSE of the three-dimensional position and rotation angle measured by the developed device is 2.6 mm and 1.5 °, respectively. The proposed device enables physical therapists to easily measure ankle motions with an accuracy as high as that of an MCS. Therefore, therapists will be able to evaluate the degree of physical disability and the effect of rehabilitation more properly and objectively than the previous measuring method using the goniometer.

In the future, we will propose a novel method of ROM display using three-dimensional graphics and compare the ROM between young adults and elderly people. Moreover, this work can be extended to analyzing of the ankle joint motions and PT exercise therapy.

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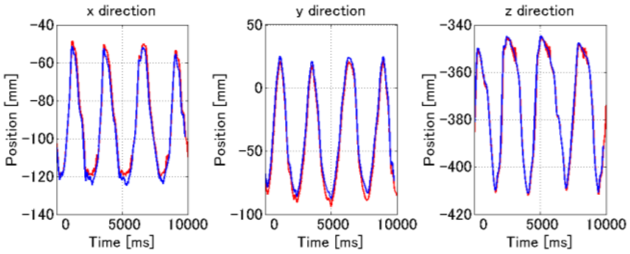
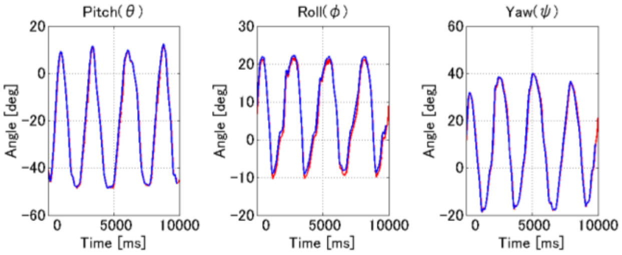
TABLE II.
THE MAXIMUM ERROR AND RMSE OF THE DYNAMIC EXPERIMENT

	Maximum error	**RMSE**
x [mm]	8.1	2.5
y [mm]	10.6	2.6
z [mm]	5.8	1.9
θ [deg]	6.3	1.5
φ [deg]	2.9	1.1
ψ [deg]	5.1	1.4



(a) Position of the foot plate as a function of time



(b) Rotation of the foot plate as a function of time

Figure 9. Comparison of $\boldsymbol{P_D}$ (blue line) and $\boldsymbol{P_M}$(red line).