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# Measurement System of Body Shift during Head of Bed Elevation Based on Robust Tracking of Mattress Edges using LIDAR

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*Abstract*— **This paper proposes a contactless measurement system for body shift on the mattress during Head of Bed (HOB) elevation to investigate detail mechanism about how body shift causes discomforts and pressure ulcer. For contactless measurement, one LIDAR captures the distance from the mattress edges to the shoulder, which means the upper part of body movement distance. The other LIDAR measures the distance to the foot, which represents that the lower part of body sliding. Since contours of mattress and body surface change dynamically during HOB elevation, the robust measurement is difficult. To overcome various changes of contour, a particle filter is used for robust tracking of the mattress edges and the foot plantar. The experiment about tracking performance and distance measurement demonstrated feasibility of our system in practical settings.**

## I. INTRODUCTION

In clinical care settings, head of bed (HOB) elevation is essential for early postoperative rehabilitation, prevention of ventilator-associated pneumonia, and implementation of enteral nutrition. In practice, knee part is elevated before HOB elevation to prevent excessive body sliding as Fig. 1. In HOB elevation, a mattress on a bed frame moves upward because of its bending, and body slides in the hip direction. These movements generate a large shear force on the body. Especially, sacrum receives the extreme shear force if the subject has a bone prominence. It is known that this situation increases a risk of pressure ulcer development because the large shear force causes ischemia [1][2]. In addition, the shear forces on the upper body and the thigh raise discomfort feelings [3]. However, detail relationship between body movement on the mattress and generated shear force is unclear. Model for relationship between bed inclination and shear force on the body is already proposed [4]. The model only considers bed inclination and does not include body shift and mattress effect. The model is insufficient to predict shear force. If the shear forces are estimated by body shift, bed inclination angle and characteristics such as height and weight, the nurses can determine the bed inclination angle by measurement of body shift to prevent excessive shear force on the patient. In order to realize this, measurement of body shift and clarification of relationship between shear force and body shift are important.

It is difficult to measure distance of the body shift. The simple approach is combination of both a wire on the body and a linear encoder. However, the wire on the body constricts body movement, and direct connection of the wire to the body is difficult in the real situation. A motion capture system is often used for body posture measurement [5]. The system needs a special room equipped with cameras and marker attachment on the body. These requirements for measurement are impractical for introduction into clinical setting during experiments. Another approach is combination of transparent mattress and camera system [3]. This approach is limited to the special mattress for measurement. The new device for measurement of body shift on a mattress during HOB elevation is desired.

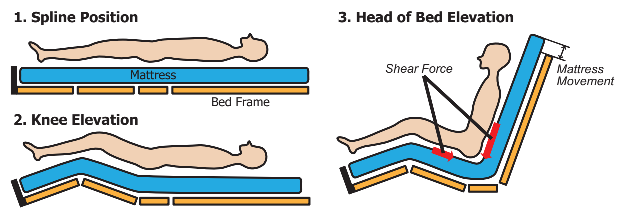


Fig. 1. Body shift during HOB elevation

Currently, distance cameras such as kinect are often used for contactless measurement of body movement. However, the measurement system should capture the body shift distances with high resolution (1 cm) because shift distance of upper body is approx. 10 cm from [3]. The distance camera system is unsuitable for body shift distance measurement. We employ a 2D Light Detection and Ranging (LIDAR) for measurement. The LIDAR measures accurate distances to objects using the reflection of infrared laser with fixed angle resolution. The device satisfies measurement distance and is strong for contour changes of the mattresses and the body because of LIDAR's large cover area by scanning. These features are suitable for measurement of body shift distance.

The measurement system should capture not only distances from sensor to body parts but also the distances to mattress edges. The mattress slides upward during HOB elevation because of bending. The movement of the mattress is different with that of the body. The relative body shift on the mattress is important to investigate relationship between the body shift distance and the shear force. The body shift distances of the upper body is different with that of the lower body because the body bends and sinks on the mattress at hip position. Measurement of shift distances of both the upper and lower body is also important. In this paper, body shift includes two shifts of both the upper and lower body.

Our research aim is to construct measurement system of relative body shift to a mattress. We also develop the robust tracking method from points captured by the LIDAR to

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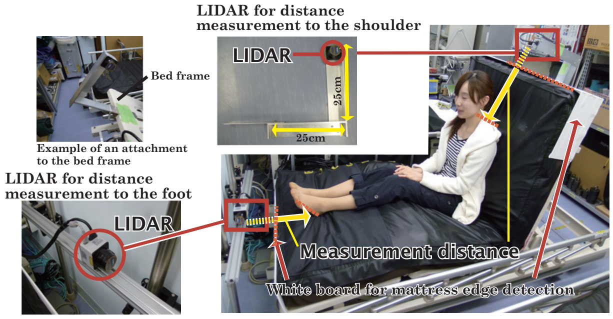

Fig. 2. Overview of System Hardware

measure body shift on a mattress robustly under sliding of the body and the mattress.

## II. Measurement system for body shift during HOB elevation

Our system employs two LIDAR to body shift measurement. One LIDAR captures the upper body movement and the other measures the lower body shifting. Ideally, use of a single LIDAR is desired to simplify measurement system. The only deployment where scan beams extend downward or obliquely downward satisfies measurement using a single LIDAR. Resolution of measurement distance decreases in this arrangement because the LIDAR is far from the body and the scan angle of LIDAR is fixed. The dynamic change of body surface according to HOB elevation and body sinking also reduces measurement accuracy because this change makes recognition of body edge difficult. Therefore, we use two LIDARs to capture the upper and lower parts of the body measurement. The measurement system is shown in Fig. 2. URG-04LX (Hokuyo Automatic Co., Ltd.) is used as a LIDAR. Maximum measurement distance is 5.6 m, distance resolution is 1 mm, measurement angle is 240 degrees, angle resolution is approx. 0.36 degree, and sampling rate is 10Hz. The device uses class 1 laser, which means that the device is safe for humans.

What body part should be measured is the problem to detect the upper body movement. The head measurement is difficult for the LIDAR because texture of hair does not reflect laser well and hair movement disturbs easily laser reflection. Thus, the system measures the shoulder instead of the head part. The other problem is that a bed frame tilts according to HOB elevation. To adapt to this frame inclination, the LIDAR is attached on the bed frame directly with a special jig (Fig. 2). On the other hand, the foot is easy to detect its contour for LIDAR and the foot movement is covered by fixed LIDAR scanning due to small knee elevation. These conditions do not require special equipment to the bed frame. Therefore, the LIDAR to measure the lower body movement is deployed in the front of the foot side edge (Fig. 2).

As mentioned Sec. I, the system measures relative distance to the mattress. Detection of the mattress edge is not easy because the edge at the upper body side slides upward and the edge at the lower tilts according to knee elevation. The contour of the mattress edge is also unstable during HOB elevation, and the edges are various among kinds of mattresses. Attachment of white board on the edges reduces the difficulty of edge detection using LIDAR. The LIDARs are connected to a laptop PC with USB cable. The software for recording distance data and visualizing raw LIDAR data is developed. We designed that the introduction of the system and use of the software are easy enough for the clinical researchers and the nurses.

## III. Distance Estimation from scan points captured by LIDAR

### A. Detection of Mattress Edge

The mattress edge is captured as a line segment by the LIDAR. The simple approach is searching the line segment by template matching. However, this approach needs long calculation time to apply various-angle templates to overall area, and angle estimation of the segment is not good in general due to discreteness of angle resolution. As another approach, Hough transformation and line fitting using least squares method are often utilized for line detection. Scan points captured by LIDAR include cluttered line segments such as a part of mattress, clothes of a subject, and other objects in the measurement environment. These confusable scan points trigger mistake of segment detection in these approaches. Fortunately, the mattress edges move and tilt slowly according to HOB elevation. The tracking approach based on filtering technique is effective to estimate accurate segment location and rotation.

As a tracking method, we use a particle filter [6], which is often employed for human tracking from horizontal LIDAR scan data. The particle filter is a kind of statistical filter for time sequence data. The statistical filter calculates posterior distribution of the state under the sensor observation, and then estimates the state as expectation value of the posterior distribution. The posterior distribution is calculated from transitional model and observation model by assuming Markov property of the state. The particle filter represents the posterior distribution as a set of particles including a weight and a state. Therefore, design of transition and observation model is important for the filter. In the current problem, the length of the segment is known and fixed because white board is attached on the mattress edge. The only center position and angle of the segment are defined as a state $(x, y, \theta)$. For transition model, since it is difficult to model the mattress edge movement and speed of movement is small, the values generated according to normal distribution with mean 0 are appended to states in the particles.

The weight of the particle is evaluated by following procedure as a observation model.

1) Conversion of the distance data to 2-dimensional data
   The distance data from LIDAR is converted into points $(x, y)$ on the plane orthogonal to bed frame.
2) Selection of points near the previous estimated location
   To reduce calculation time, the points that are located within twice length of white board are selected.
3) Calculation for each particle

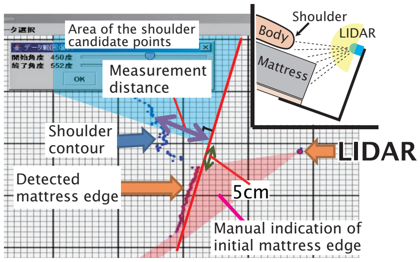


Fig. 3. Distance measurement from the mattress edge to shoulder

a) Distances from the segment represented by the particle state to all selected scan points are calculated.
b) The distances are sorted in descending order.
c) The distances $d_i | i = 1 \ldots m$ are selected from the sorted distances. If the number of chosen point $n$ is less than $m$, $d_{n \ldots m}$ is occupied with long distance (e.g., 1 m).
d) The weights are calculated as $\prod_{i=1}^{m} exp(\frac{-{d_i}^2}{\sigma^2})$

In weight calculation, only the fixed number of scan points are used to reduce the wrong evaluation caused by outlier data and to prevent that the small number of scan points increases weight. The parameters are defined as follows empirically. The number of points for selection is 70, $\sigma$ is 50 in 3)-d), and the number of particles is 500. From preliminary experiment, we confirmed that the calculation time is less than 100 ms, which is LIDAR sampling rate. This fact means that the calculation is finished during one sensor data capturing.

Estimation of initial state is important for tracking problem. Fortunately, once the system is introduced into the clinical setting, the mattress edge position is the similar to the initial position. Thus, in the system, the segment position is taught by hand to the system at first time. The tracked segment of the mattress is used for measurement of the body shift distance as the next subsections.

### B. Measurement of distance from the edge to shoulder

In the system, the upper body movement is measured as the distance from a mattress edge to the shoulder of a subject. While the mattress edge is detected as above section, detection of the shoulder is difficult. The shoulder shapes are various with clothes and individual characteristics. To avoid this variety, we adopt simple approach that the system detects the top of the shoulder contour. The distance is measured by three steps in Fig. 3: i) Calculation of line (red line in the figure) corresponding to the detected edge, ii) Calculation of distance from the line to points in the area of shoulder contour candidates (points in the cyan area), and iii) Selection of the minimum among the calculated distances.

### C. Measurement of distance from the edge to foot

What distance is regarded as the distance from edge to the foot of a subject is difficult problem. Ideally, the edge to the heel is preferable because the heel position is stable in various foot angles. It is difficult to detect the heel position directly from only 2-D contour of the foot from LIDAR. On the other hand, the foot plantar is regarded as the segment.

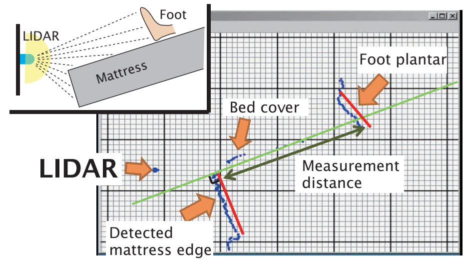


Fig. 4. Distance measurement from the mattress edge to foot

The same approach for the mattress edge is applicable to this segment. We also use other knowledge that the mattress surface is orthogonal to the mattress edge at the end point of the edge. Finally, the distance is measured by three steps in Fig. 4: i) Detection of the foot plantar using the same method as mattress edge tracking (red line in the figure), ii) Finding the mattress surface, which is regarded a line as normal to the mattress edge and passing the end point of the edge (green line in the figure), and iii) Calculation of distance from the end point of the mattress edge to the point of intersection between the foot line and mattress line.

## IV. Experiments of Body Shift Measurement

### A. Measurement Condition

To evaluate our measurement system, the body shift distances were measured in the situation that imitates clinical setting. An air cell mattress whose thickness is 15 cm was used. The all inner pressures of air cells were 3 kPa. The subjects put on the same cotton clothes and lay on the mattress without sheets. The measurement protocol used is as follows. First, a subject lies on the mattress. After 5 second, knee is elevated to 20 degree. After knee elevation, HOB is elevated to 75 degree. This protocol is repeated three times per subject. The lying position is fixed at all trials. The bed angle is easily estimated by the elapsed time from the initial of the experiment. The study protocol is approved by the Ethical Committee of the Graduate School of Medicine, The University of Tokyo (#3551).

### B. Comparison of Body Shift Measurement with another Device

The measurement distance using our system was compared with the measurement using a linear encoder that needs wire attachment. In the experiment for shoulder measurement, the encoder was located near the LIDAR, and a wire of one encoder was connected to the white board on the mattress edge of the head part because it is difficult to attach the wire to the shoulder directly. In the experiment for foot measurement, the encoder is located by the same way, and the wire was linked to the slipper-like jig which is attached on the foot. Both the system and the encoder captured relative distance from initial position. Note that the linear encoder may measure more accurately than our device, but the encoder cannot measure true values, because the wire tension affects the edge and the foot angles and it is difficult to maintain the wire parallel to mattress surface during HOB elevation. The data about one subject were collected.

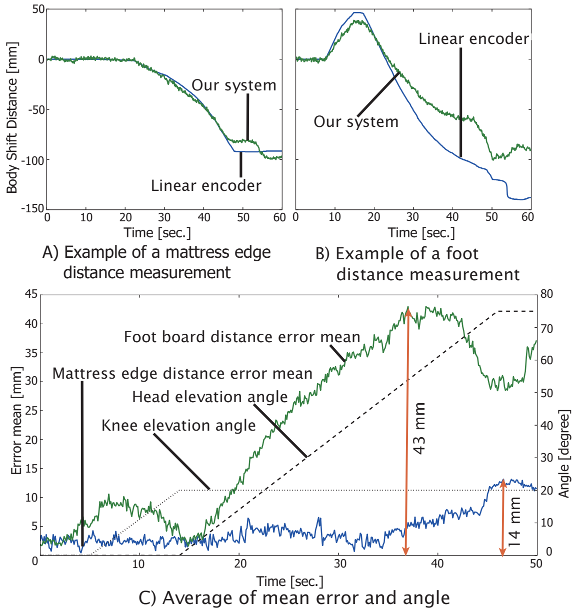


Fig. 5. The comparison result of body shift measurement between our system and the linear encoder

Fig. 5-A) and Fig. 5-B) shows typical trend of the distance change at the mattress edge and the foot, respectively. Fig. 5-C) illustrates the error tendency during HOB elevation. The error is defined as the absolute difference between results obtained with our system and the encoder data. The mean error of mattress edge measurement is approximately within 1 cm. The result demonstrates our tracking method robustly detects the segment of the edge. The error is sufficient to measure body shift on the mattress because the final body shift distance is known as approx. 10 cm [3]. On the contrary, the foot distance measurement is worse than the edge. The error increases according to HOB elevation. Distance estimation using our system depends on the assumption that mattress edge is orthogonal to the mattress surface (i.e., the angle between mattress edge and surface is strictly 90 degree). However, this assumption is not true in high angle of HOB elevation due to deformation of the mattress. Especially, the air cell mattress is easy to transform. Thus, this deformity causes the mistake of estimation of mattress surface, which decreases the foot distance measurement performance. However, since the foot error is smaller than the total foot movement known as before, our system is able to confirm body shift tendency.

### *C. Confirmation of tracking robustness*

To confirm the practical feasibility of our system, we provided the system for a nursing researcher who wants to measure the body shift distance to investigate how long body shifts on the air mattress. She measured 27 healthy subjects (15 female, age: 26.3 $\pm$ 3.0 years, height: 1.65 $\pm$ 0.08 m, weight: 58.6 $\pm$ 13.5 kg). The total 27 x 3 = 81 trials were collected.

The result is shown in Table. I. In the table, the failure means the system outputs obviously wrong distance. In the measurement failure of shoulder distance, hair of the subject interrupted the laser beams to the shoulder. The slight head movement intercepted the laser beams to the shoulder, which caused 14 measurement failure within 2 sec. The foot edge detection was missed 6 times by the foot movement to outside of the LIDAR scan plane. In practice, if missing of the shoulder and the foot occur during the measurement, the measurement is easily retried after adjusting the LIDAR position. This result is good enough to measure the body shift. The shift distances of upper body and lower body differed. This may mean that body sinking and sliding of the lower part of the body. This posture may generate large shear force on the body.

TABLE I
THE RESULTS OF TRACKING

| | Failure | Failure within 2sec. | Success | Mean (and SD) of shift distance after HOB (mm) |
|---|---|---|---|---|
| Shoulder | 1 | 14 | 66 | 32.8 (22.6) |
| Foot | 6 | 0 | 75 | 126.6 (47.2) |

The nursing researcher is not familiar with complex medical device, but she can employ the system easily in the experiment. This means practical feasibility of our system for the nursing researchers.

## V. CONCLUSION

We constructed the contactless measurement system for shift distance of the upper and lower body on mattress during HOB elevation. The system contains two LIDARs to capture the distances. One LIDAR attached on the bed frame measures the distance from the mattress edges to the shoulder and the other deployed in the front of foot side of bed captures the distance from the mattress edge to the foot. We also developed measurement algorithm for the distances from scan points by tracking the mattress edge based on the particle filter. Performance comparison with a linear encoder and measurement about multiple healthy people were conducted. The experiments demonstrated that our system can measure the distances robustly and stably and the system is easy enough for a nursing researcher to use. In future work, we will investigate relationship between the body shift and external forces (interface pressure and shear force) on the body using our developed system.

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