Libra3D: Body Weight Estimation for Emergency Patients in Clinical Environments with a 3D Structured Light Sensor

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***Abstract*— This paper describes the application of a weight estimation method for emergency patients in clinical environments. The approach applies established algorithms for point cloud processing and filtering to data from a low-cost, structured light sensor. A patient's volume is estimated on the basis of their visible front surface. The approach is currently being tested in the workflow of the emergency room at the Universitätsklinikum Erlangen, Germany. Preliminary results show the accuracy of the approach in relation to other conservative means of weight measurements, for example, by physicians and anthropometric measurements.**

I. INTRODUCTION

In emergency situations, body weight adapted dosage is crucial for many drugs. This is particularly important if drugs are known to have a narrow therapeutic range with decreased efficacy in lower dosages and an increased risk for possibly severe adverse effects in higher dosages. Many emergency patients are unable to communicate information on their body weight because of their symptoms, e.g., decreased consciousness or neurological disorders, or because they simply do not know their own body weight. In addition, severe injuries or motor symptoms prohibit easy weighing procedures for many patients. Certain diseases like ischemic stroke are associated with a very narrow time window for treatment and do not allow time to weigh each patient in the emergency situation. Therefore, visual estimation of the patient's body weight by the attending physician in the emergency room has become routine worldwide. This approach bears the risk of estimation errors [1]–[5] and may result in dosing errors, which has been shown for weight-based emergency medications [6], [7]. Less complicated and more precise methods to evaluate body weight are required for emergency patients to minimize potential dosing errors. The time required to evaluate body weight should be as short as possible and new methods should be easy to integrate into the practical processes of an emergency room to avoid treatment delays.

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Fig. 1. Emergency room at the Universitätsklinikum Erlangen with Microsoft Kinect and Optris PI400 (not used in this paper) mounted on the ceiling.

Libra3D[a] was designed with the goal of creating a new contact-free method to evaluate body weight based on visual sensor technology. Furthermore, feasibility and accuracy of this method were also evaluated. The system uses a 3D structured light sensor, see Figure 1. Data was collected in the emergency room of the Neurological Department of the Universitätsklinikum Erlangen, Germany. The system is located in the ceiling above the patient's stretcher and connected to a computer. By pressing a button, data from the sensors are collected to detect the patient's position and the stretcher surface, and to determine the patient's body volume. Based on this body volume estimate, the body weight is calculated.

The paper is structured as follows: Section II discusses related work for body weight estimation with a focus on the applicability in emergency situations. In Section III, the clinical environment and the experiments are described. Section IV describes the process chain of body weight estimation. Section V presents the experiments and preliminary results of *Libra3D*. The results are compared to weight estimates by physicians, patient's self-estimates, and estimates from an established anthropometric method based on body height, waist circumference, and hip circumference. Finally, section VI concludes with an outlook on future work and planned improvements.

[a]*Libra3D* is derived from the Latin word *libra* for scale.

II. RELATED WORK

A. Body Weight Estimation

Weight can be measured based on different physical principles. The most common way is to use a scale. Spring scales reach an accuracy of 0.1 % easily. The weight of reclining patients on a stretcher or patient table can be acquired, in principle, by different kinds of force sensing or alternatively by detecting the mass of inertia. Scales located on the floor that can weigh the whole stretcher with the patient on it by measuring the vertical force of gravity are available for hospitals. However, as the exact tare of all stretchers in use along with their individual accessories is not usually known precisely, there is a high uncertainty of measurement associated with this method.

In patient tables for medical imaging applications there are some alternative methods in use or proposed for patient weight acquisition, mainly used to improve the imaging control parameters. In some cases the motor current I or the hydraulic pressure p in the lifting device is measured, which is proportional to the vertical force $F \sim I$ caused by the table itself and the patient on it. Due to friction and other disruptive effects, the weight determination is usually very rough [8]. An alternative method is to accelerate the table top with the patient on it by a pre-determined force F for a short distance x in the horizontal direction. From the resulting velocity progression Δv the mass of the patient body can be calculated by using the equation of motion $F = m \cdot a$.

Estimating body weight w from body volume v requires knowledge about body density ρ. To measure human body density ρ there are commonly used methods like hydrodensitometry or air displacement plethysmography [9], but they are time-consuming and therefore poorly suited to clinical practice.

Popa et al. showed the measurement of body density ρ by bioelectric impedance rating [10]. Body density varies greatly from patient to patient, and is specifically dependent on gender and age, as shown in studies by Durnin and Womersley [11]. Based on 481 patients, the highest body density was measured with 1,082 kg/m^3, while the lowest was 968 kg/m^3. Males have a slightly higher body density and the older a person is, the lower is his density. Furthermore, Wang et al. showed differences in percentage body fat $\%\text{BF}$ and density ρ between different ethnic groups [12].

Besides by direct direct measurement, body weight w can be estimated from related anthropometric features. Sendroy and Collision produced the following the correlation between body weight w, length l, surface s, and volume v in a study with over 700 patients in 1966:

$$w = \left(\frac{\frac{v}{s} - c}{a} \right)^b \cdot l, \tag{1}$$

where the parameters a, b, and c represent empirical setting options for different ages, genders, and ethnic groups [13]. Similar, Lorenz et al. developed a formula with up to nearly 6 % accuracy for weight approximation for stroke patients [14]. They used body height l, waist circumference w, and hip circumference h — all in centimetres. The coefficients for the equation

$$w = A + l \cdot B + w \cdot C + h \cdot D \tag{2}$$

differ according to the patient's gender. However, measuring the circumferences on a human body may require gratuitous movements, which could be detrimental in cases of fractures or internal injuries.

B. Body Weight Estimation with Optical Sensors

Body volume can be determined without physical contact by different methods. Only a few approaches attempt volumetric reconstruction on the basis of measuring only the front surface. Pirker et al. employed sixteen stereo cameras around a stretcher [15]. and additional projectors are required for complete illumination. The back side of the body must be complemented by a parametric human model and the final images created are filtered for noise reduction. Finally, the volume is calculated using cross sections along the body. This method is difficult to use in practice, because the high number of cameras around the patient's bed could easily impede physicians while treating patients.

Cook et al. presented a framework based on a structured light sensor for radiation dose estimation in CT examinations [16]. In preliminary experiments they showed results for five persons standing in front of a structured light sensor. The measured volume of the patient differs according to different positions of their arms. With the help of skeleton tracking, Velardo and Dugelay presented a computer vision system to assess the health of a person using a structured light sensor [17]. Apart from the age of the proband, the sensor records anthropometric features from arms, legs, and the body to calculate the weight of a person. Trained with statistical models from a medical database, the system provides information about obesity and nutrition to the user.

All methods for visual weight estimation presented here can segment the patient efficiently, due to an adequate distance to the background and a fixed position of the patient. To date, a precise body weight estimation technology with low time requirements that does not require physical contact for emergency patients on a stretcher is not available.

III. HOSPITAL INTEGRATION

A. Workflow for Weight Study

For the integration of the test bed in the clinical environment a few modifications to the trauma room were made. Sensors were placed in the ceiling and connected to a computer beside the stretcher for controlling, processing, and visualization. Markers on the floor indicate the approximate position of the stretcher in the room. While the stretcher has a size of 2×1 m, the markers on the floor span an area of 2.3×1.3 m.

The patient is brought to the emergency room on the stretcher. The stretcher must be placed inside the marked rectangle on the floor. The handlebars on the stretcher can be raised for patients with seizures to prevent them from falling down, see Figures 1 and 2a. Every patient is identified with

(a) Schematic of patient on stretcher with handlebars: different bounding boxes around the patient are used for filtering and segmentation.

(b) Raw sensor data from sensor's view with patient on stretcher at the Universitätsklinikum Erlangen.

(c) Patient extracted from stretcher with triangle mesh in detail: the patient is segmented from the stretcher with the illustrated plane in blue.

Fig. 2. Patient on the stretcher in the trauma room.

a unique bar code placed on every document concerning the patient's anamnesis or treatment. Therefore, the physicians have to enter the number of the bar code or scan it, to provide explicit identification. Other information concerning the patient can be added after treatment, if time is constrained.

The weight estimation algorithm takes a single frame from the structured light sensor and forwards it to further processing as described in Section IV. Within a few seconds the physician can read the estimated weight on a monitor. Patients have to lie flat on the stretcher, with their arms beside their body and legs not crossed, as illustrated in Figure 2a. To compare the different methods for weight estimation in Section V,the patients were weighed on a spring scale, if they were able to stand, or on a stretcher scale, afterwards.

B. Limitations

There are some limitations to *Libra3D's* weight estimates due to its reliance on optical technologies alone. We expect to have a bigger relative measurement error for very muscular, obese, or skinny patients, because of variations in body density. The patient has to be completely in the field of view of the structured light sensor and must not be covered by a blanket. Loose and thick clothing should be removed from the patient, which is usually already the case for easier treatment. At the current stage of development, our approach localizes a single plane in the point cloud in order to estimate the contact surface between the patient and the stretcher as reference for the weight estimation. Although the stretcher has a back rest, it should be aligned coplanar to rest of the stretcher to provide a surface similar to a plane. The optical weight estimation system cannot currently be used for patients who cannot be positioned with their back to the stretcher, for example, because of back pain or fractures.

IV. Approach

A. Patient Segmentation

Based on the previously described markers on the floor, an axis-aligned bounding box filters points from the point cloud $\mathbf{C}$ to eliminate possibly wrong points of the patient or the reference plane and to save computation time, see Figure 2a. In the next step, the minimal bounding box including the stretcher and the patient is defined with length l_{bb}, width w_{bb}, height h_{bb}, the centroid c, and the orientation $\mathbf{R}_{3\times3}$.

Out of this bounding box, the medical stretcher is localized by RANSAC [18], and therefore modeled as a plane with the Hesse normal form $\vec{P} = (\vec{n}\ d)^T$ based on the normal of the plane $\vec{n} = (n_x, n_y, n_z)^T$ and the distance to the origin d. To prevent errors in plane detection, the minimal bounding box is reduced in height h_{bb} and width w_{bb} to filter out the handlebars at the edges of the stretcher, see Figure 2.

The reference plane $\vec{P}$ is then verified in terms of its distance to the sensor d and its angle of the normal $\alpha(\vec{n})$ to the camera axis. If several planes are found, the plane $\vec{P}$ with the biggest area is used to segment the patient from the stretcher. In addition, points behind the plane are filtered out. Checking if an arbitrary point $\vec{p} \in \mathbf{C}$ is in front of the plane $\vec{P}$ is done with $d(\vec{p}, \vec{P}) > 0$ and

$$d(\vec{p}, \vec{P}) = \vec{p} \cdot \vec{n} - d. \tag{3}$$

Under ideal circumstances, the point cloud $\mathbf{C}$ now only consists of points belonging to the patient after filtering. Additionally, the points in the plane that are obscured by the patient are taken to define the patient's back surface.

B. Body Volume Estimation

A mesh $\mathbf{M}$ consisting of triangles $\mathbf{T}$ is generated for the points of the patient's surface, see Figure 2c. For a smoother surface, the point cloud is optimized with a bilateral filter [19]. The triangle mesh $\mathbf{M}$ for the back side of the patient is generated by projection of the front surface along rays from the sensor to the plane. Between both meshes, the volume v is calculated polyhedron-wise: let $\vec{a}_i$, $\vec{b}_i$ and $\vec{c}_i$ be the vectors spanning the tetrahedron from the focal point to the front surface and $\vec{a}_i^r$, $\vec{b}_i^r$ and $\vec{c}_i^r$ be the vectors spanning the tetrahedron from the focal point to the back surface. Subtracting the front tetrahedron from the tetrahedron facing the back defines polyhedrons associated with the patient's volume, see Figure 2c. Adding up the polyhedron volumes, one obtains the patient's volume v as follows, while N is the number of surface triangles $\mathbf{T}$:

$$v = \frac{1}{6}\sum_{i=1}^{N} |\vec{a}_i^r \cdot (\vec{b}_i^r \times \vec{c}_i^r)| - |\vec{a}_i \cdot (\vec{b}_i \times \vec{c}_i)| \tag{4}$$

C. Body Surface Estimation

With the help of the triangle mesh $\mathbf{M}$ the surface s is computed. For an arbitrary triangle $\mathbf{T} \in \mathbf{M}$ the area is calculated using with the Heron's formula with the semiperimeter $m = \frac{ab+ac+bc}{2}$, see Figure 2c.

$$\begin{aligned} ab_i &= |\vec{a}_i - \vec{b}_i| \quad ab_i^r = |\vec{a}_i^r - \vec{b}_i^r| \\ ac_i &= |\vec{a}_i - \vec{c}_i| \quad ac_i^r = |\vec{a}_i^r - \vec{c}_i^r| \\ bc_i &= |\vec{b}_i - \vec{c}_i| \quad bc_i^r = |\vec{b}_i^r - \vec{c}_i^r| \end{aligned} \tag{5}$$

$$\begin{aligned} s = &\sum_{i=1}^{N} \sqrt{m_i(m_i - ab_i)(m_i - ac_i)(m_i - bc_i))} + \\ &\sum_{i=1}^{N} \sqrt{m_i^r(m_i^r - ab_i^r)(m_i^r - ac_i^r)(m_i^r - bc_i^r))} \end{aligned} \tag{6}$$

For the surface of the human body, all areas of the triangle mesh from the frontal surface and the plane beneath are summed up.

D. Body Length Estimation

Body length l is measured from foot to head. The patient's body does not have to be to be oriented parallel to the stretcher, therefore the body length is calculated on the basis of the patient's segmentation. From the remaining points, see Figure 2c, a principal components analysis (PCA) is performed. The longest axis is taken for the body length l.

Currently, a body length estimate is used as a control for the algorithm. If the patient's body length is outside of the range of 1.50 m to 2 m, the weight estimation algorithm is not reliable, since the stretcher is only 2 m long. Parts of the body, e.g. head or feet, might hang over the stretcher and therefore produce an error in weight estimation.

E. Body Weight Estimation

Based on the previously calculated volume v between the mesh and the reference plane, the body weight w is calculated with a fixed coefficient for the body density ρ with $w = v \cdot \rho$.

We obtained the best results for the experiments in Section V with a density of $\rho = 1{,}040\,\mathrm{kg/m^3}$. In the study of Durning and Womersley [11] the mean density $\bar{\rho}$ over their 481 patients was also near this value for the body density.

Algorithm 1 summarizes the sequence in calculation of the body weight w.

Algorithm 1 Algorithm for body weight estimation.

procedure ESTIMATEBODYWEIGHT(cloud $\mathbf{C}$)
  $i \leftarrow$ valid indices of $cloud$ from $boundingbox$
  $BB_{min} \leftarrow$ calculate minimal bounding box $\in i$
  $\vec{P} \leftarrow$ plane from RANSAC($\mathbf{C}$, BB_{min})
  if $angle(\vec{P}) > TH$ **then**
    break
  end if
  $\mathbf{M} \leftarrow$ mesh from points belonging to patient
  $v \leftarrow$ get volume of mesh $\mathbf{M}$ to reference plane $\vec{P}$
  $w \leftarrow v \cdot \rho$
  return w
end procedure

V. EXPERIMENTS AND RESULTS

The experiments are based on the data set recorded from the emergency room at the Universitätsklinikum Erlangen, Germany, between June and September 2014. The data set contains $n_f = 51$ female and $n_m = 59$ male patients – in total n = 110 valid patients – admitted to the emergency room. Patient clinical presentation was not recorded in the data set. Patients of mixed age, physique, and symptoms were included, though none of the patients had amputations. Patients were excluded from the study if basic conditions were unsuitable, such as if the body was partially covered or not correctly placed in the bounding box. Physicians took up to three measurements, if the algorithm returned obviously wrong values for weight estimates. For analysis, the value closest to the physicians opinion was taken in cases where several measurements were taken. In two cases the localization of the reference plane failed; these two measurements were excluded from the data set.

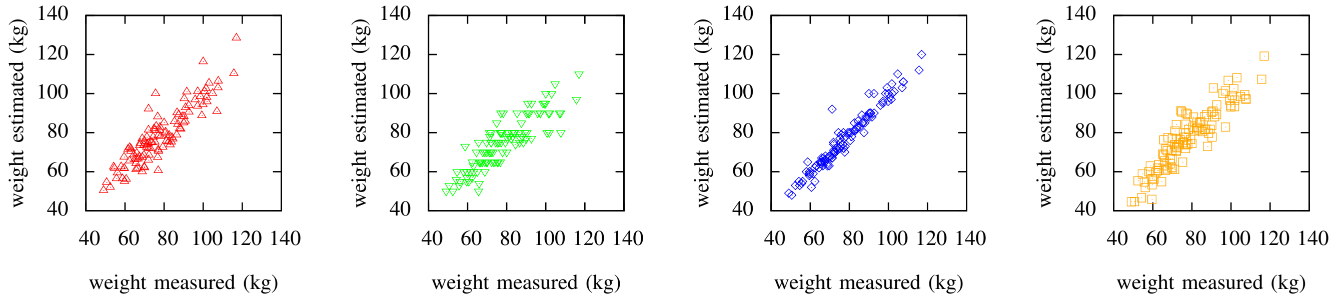
Table I provides an overview of the measurements recorded in the data set.

The diagrams — see Figure 3 — illustrate the results in comparison to other estimation methods by plotting the measured and the estimated weight. All plots show linear approximation, but differ in their standard deviation σ. If they could answer, patient's estimates had the highest accuracy, followed by the Lorenz weight estimation method [14].

		min	max	mean	σ [a]
Weight	(kg)	49	117	78.03	15.03
Age	(y)	19	86	53.05	17.30
Body Size	(m)	1.49	1.97	1.71	0.1
Hip Size	(m)	0.81	1.40	0.99	0.10
Waist	(m)	0.61	1.36	0.93	0.12
BMI	(kg/m^2)	17.92	40.48	26.41	4.23

[a] standard deviation

TABLE I
OVERVIEW OF PATIENT MEASUREMENTS IN THE DATA SET.



(a) Libra3D (b) physicians (c) patient (d) Lorenz

Fig. 3. Comparison of weight estimation by *Libra3D*, *physicians*, the *patient's* answer and the Lorenz weight estimation method [14].

	relative error ϵ (%)				absolute error η (kg)				dosage (%) [a]		
	min	max	mean	σ	min	max	mean	σ	under	over	correct
Libra3D	-21.31	32.26	1.02	8.59	50.44	128.44	78.48	14.85	7.27	13.63	79.10
physician	-25.71	24.36	-3.74	8.71	50.00	110.00	74.58	13.04	25.45	6.63	68.18
patient	-14.19	29.21	-1.34	4.87	48.00	120.00	77.03	15.59	1.81	2.72	95.45
Lorenz	-22.88	22.57	-1.06	8.19	44.55	119.19	77.13	15.42	10.90	9.10	80.00

[a] relative error higher than 10 % is considered to be an overdose, while a relative error lower than -10 % is considered an underdose

TABLE II
EXPERIMENT RESULTS.

Comparing the methods by *physicians* and *Libra3D*, they are in the same range for over or underdosed patients while the estimation by algorithm provides more correct dosed patients, but *Libra3D's* algorithm resulted in more correctly dosed patients, see Table II.

To examine the effect of different body densities, Figure 4b illustrates the correlation between body-mass-index $\text{BMI} = l/w^2$ as an indicator for the percentage body fat $\%\text{BF}$, to the relative error ϵ in weight estimation. Rankinen et al. showed that there is a correlation between the BMI, body fat and therefore the body density ρ [20]. Because of a lower density $\rho \sim m$, we expect a lower relative error in estimation for obese patients, as well as a smaller relative error for underweight patients.

The plot shows a slight increase of the body weight error. As shown by Durnin and Womersley the density can fluctuate in a range of 968 kg/m^3 to 1,082 kg/m^3 [11]. With our fixed density of $\rho =$1,040 kg/m^3 we are close to the mean value of this range, and can predict a maximum error of 6 % as a result of uncertainty in body density ρ.

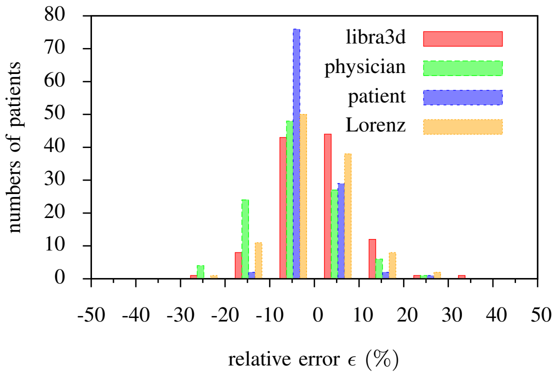
A. Encountered Problems

Essentially, the results in weight estimation are strongly correlated to the results of the reference plane estimation. Minor errors in the distance d or the angle α of the reference plane lead to a large absolute error η in weight estimation. Especially parts of the stretcher on the top and bottom of the reclining area should be visible to the sensor to prevent errors in plane localization. For these preliminary results we also did experiments addressing the measurement noise of the sensor. If the reference plane for volume estimation is the same, the difference in volume estimation is negligible. Though it can happen that the reference plane is not found with the same parameters due to measurement noise.

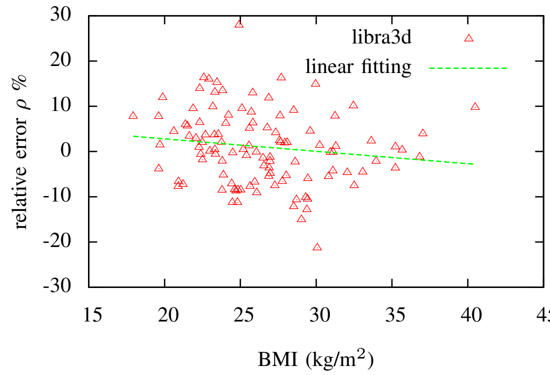
In laboratory experiments we encountered a slight difference in weight estimation due to variations based on breathing. The lung volume of a human is in the range of 2 to 8 liters and is also related to age, sex, body height, and state of health [21]. Patients who have inhaled, have a slightly higher estimated weight, but the estimate is less than 4 kg too high. Experiments in the future will be designed to address breathing detection estimation based on multiple sensor readings.

VI. CONCLUSION AND FUTURE WORK

This approach showed the body weight estimation based on a 3D structured light sensor for patients in a clinical environment. The algorithm uses the measured body volume v and a fixed density ρ to compute the body weight w. Experiments with 110 patients showed reliable results in comparison to the weight estimation from a physician. Although the system is not better than established anthropometric weight estimation like the method developed by Lorenz et al. [14], it needs less computation time. Compared to the physicians estimation, there were fewer over- or underdosed patients based on the estimate from the *Libra3D* system. The next step is a clinical trial with 2000 emergency patients at the Universitätsklinikum Erlangen, Germany. It will test the system for clinical applications and provide data to optimize the contact-free weight estimation. For better segmentation results further algorithms and sensors will be tested. A thermal camera fused with the structured light sensor will support features to segment the patient using body temperature as differentiated from the room temperature stretcher, see Figure 1. The



(a)



(b)

Fig. 4. Results of experiments: Histogram for comparison of different weight estimation methods (a). Correlation of BMI and relative error in weight estimation to prove different densities (b).

segmentation of single body parts can help to calculate the weight with different densities. To develop the method for more general settings, a volumetric reconstruction of the human body can help to determine body weight without a reference plane. This is set for future work.

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