Inertial Measurement Unit to Segment Calibration Based on Physically Constrained Pose Generation

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Abstract: The accuracy of a motion capture (MoCap) system based on inertial measurement units (IMUs) depends on the IMU-to-segment (I2S) calibration, in which the IMU alignment relative to a body segment is calculated using a reference pose such as a standing T-pose. This study proposes a novel I2S calibration system for a reliable MoCap system. In this system, the reference pose for calibration is constrained by physical objects, and this pose is generated by an optimization-based method which incorporates the IMU measurements with the physical constraints between the body and the object. To demonstrate the system, we estimated the chair-sitting and half-squat motions based on the calibration using a chair and estimated the center-of-mass movements of a rider when riding a motorcycle based on the calibration using a motorcycle. The experiments confirmed the improvements of the motion estimation accuracy by the proposed system, in both chair-sitting and half-squat motion and center-of-mass tracking of a rider. Furthermore, the proposed system enables the I2S calibration using product-use poses.

Key Words: inertial measurement unit, calibration, motion capture, digital human, motorcycle.

1. Introduction

Full-body motion capture (MoCap) systems based on inertial measurement units (IMUs) are widely used in computer graphics, rehabilitation, and ergonomic product designs [1]. As they require no optical sensors, they are available in everyday surroundings such as daily-living, working, and outdoor environments.

The motion estimation accuracy of the IMU-based system is lower than that of marker-based systems [2]–[4]. Fatal error factors are sensor drift by magnetic disturbances [5], skin deformation artifacts caused by joint motions [6], and poor quality of the IMU-to-segment (I2S) calibration [7],[8]. The I2S calibration, which estimates the IMU alignment relative to the corresponding body segment, must be performed prior to measurement [9].

Researchers have developed several I2S calibration algorithms that suppress the aforementioned errors [9],[10]. I2S calibration is often performed by single-pose calibration [1],[11], although multiple reference poses have reportedly improved the alignment [12]–[14]. These approaches assume a specific reference pose of the subject, such as an N-pose or a T-pose. However, this assumption is not always satisfied in practice [8]. The calibration quality is affected by the accuracy and repeatability of the reference pose, which depends on the body size, joint restrictions, and other physical properties of the subject. For example, Robert-Lachaine et al. reported that in T-pose calibration, the average angle error of the pelvis joint exceeds 10 degrees. Therefore, the reference pose must be designed for ensuring both repeatability and versatility to cope with various subjects.

In clinical studies, I2S calibration is based on functional movements such as knee rotation around the sagittal plane [15],[16]. Similarly, Palermo et al. proposed a calibration method for leg-motion tracking based on human standing, sitting, and lying poses for leg motion tracking [12]. In these studies, the movements or poses were designed with anatomical insight, so were suitable for estimating three-dimensional (3D) anatomical joint angles, especially those of the knee and hip joints. However, reproducing specific functional movements without the help of experts is a difficult task [7]. In addition, the calibration poses should be minimally intrusive for subjects with different physical abilities.

As discussed, an accurate and lowly intrusive calibration method is demanded, especially when measuring daily-living motions. From this viewpoint, Robert-Lachaine et al. reported that single-pose calibration with chair sitting pose increases the I2S calibration accuracy without intruding on the subject [3] because the subject movements are restricted by a physical object (the chair). However, to standardize the sitting pose, their approach requires a custom-made chair with adjustable seat height and armrest that fits the body sizes of different subjects. The calibration method must be designed to accept arbitrary objects for MoCap in daily-living environments. Typical examples are objects in the living environments of the subjects such as chairs and sofas, and products used by the subjects such as automobiles, wheelchairs, and motorcycles.

This study presents our novel I2S calibration system based on physically constrained subject poses. The poses are constrained by arbitrary objects in daily-living environments, such as chairs and sofas, and products used by the subjects such as automobiles, wheelchairs, and motorcycles.
as chairs. The proposed system refines the I2S calibration results by a subsequent calibration step called constrained I2S calibration. The reference pose is automatically generated by an optimization algorithm that incorporates the IMU measurements with the physical constraints between the body and the physical object.

The basic performance of the proposed system was validated in a preliminary experiment using a chair and the chair-sitting pose for the constrained I2S calibration. The proposed system was then applied to riding-motion estimation using the riding posture on a motorcycle for the constrained I2S calibration.

The features of our proposed calibration system are summarized below.

- The proposed system achieves higher pose estimation accuracy than single-pose calibration using standing pose.
- The proposed system is applicable to motion capture in daily-living environments because it requires no specific functional movements, intrusive postures, custom-made equipment, or adjustment for body size variation.
- The reference pose of the constrained calibration is automatically generated by incorporating the IMU measurements with the physical constraints. Therefore, it reflects the actual motion of the subject.
- The proposed system enables the calibration using the product-use poses such as motorbike riding poses.

The rest of this paper is organized as follows. Section 2 introduces the details of the proposed system. In Section 3, the preliminary experiment using the sofa and its results are described. In Section 4, the proposed system was demonstrated and validated using the motorcycle. Finally, Section 5 shows the conclusions and future work of this study.

2. Method

2.1 Overview

The proposed system is overviewed in Fig. 1, showing the calibration based on the chair and chair-sitting pose as an example. First, as shown in (A1) of Fig. 1, an individual digital human model (DHM) is constructed. Next, as shown in (A2) of Fig. 1, the rough I2S calibration is performed using a manually created single standing pose. The subject is then asked to use the physical object. While the subject is using the object, as shown in (A3) of Fig. 1, the constrained pose of the DHM is generated by an optimization-based motion estimation algorithm [11] under the physical constraints of the DHM fitted to the object. The generated DHM’s pose is used as the reference pose in the constrained I2S calibration step as shown in (A4) of Fig. 1. Finally, as shown in (A5) of Fig. 1, the subject’s motion is estimated using the refined calibration results obtained from step (A4). The details of each process are described in the following subsections.

2.2 DHM Construction

Prior to the measurements, an individual DHM is constructed from the body height \( h \) and weight \( w \) of the subject based on the Japanese body size database [17]–[20]. In the method [17]–[19], by applying the principal component analysis to the body size database [20], the following matrix \( W_{N \times N} \) is obtained:

\[
q_N \cong W_{N \times N} t_N,
\]

where \( N \) and \( t_N \) represent a number of body dimensions and principal component score vector (column vector containing \( N \) elements), respectively. An element of column vector \( q_N \) corresponds to each body dimension. The first and second elements of \( q_N \) correspond to the body height and body weight, respectively [19]. Given two body dimensions \( q_2' = [h, w] \), the corresponding score vector \( t_2' \) is obtained by:

\[
t_2' = (W_{2 \times 2})^{-1} q_2',
\]

where \( W_{2 \times 2} \) is the upper left submatrix extracted from \( W_{N \times N} \) whose rows and columns correspond to the index of given body dimensions in \( q_N \). Finally, all of the body dimensions \( q_N' \) are obtained by:

\[
q_N' = W_{N \times N} [r_N', 0, \ldots, 0]^T
\]

In this study, the total number of the body dimensions \( N \) is 93. More details are described in the literature [17]–[19].
The model consists of a link structure with 48 degrees of freedom and a mesh surface reproducing the skin deformations [18],[19]. Next, 15 IMUs are attached on the body segments to be measured. The IMUs can be located on any point on the segment and at any alignment because the IMU alignment is estimated in the I2S calibration processes (Fig. 1, (A2) and (A4)).

2.3 Rough I2S Calibration

Based on the single standing pose, the IMU alignments relative to the body segments are calculated by the I2S calibration algorithm. The calibration matrix \( R^C_i \) for the \( i \)th IMU is calculated as
\[
R^C_i = R^t_i (R^t)^{-1},
\]
where \( R^t_i \) and \( R^t \) are the \( 3 \times 3 \) rotation matrices representing the orientations of the \( i \)th IMU and the proximal joint of the corresponding body segment, respectively. The matrix \( R^t \) is predefined manually by assigning a standing pose (such as a T-pose) to the DHM [8]. At the same time, the coordinate system of the DHM is aligned to the subject using the arm rotation axis, as reported in the literature [8].

As discussed in Section 1, the subject pose can deviate from the reference pose of the DHM. The pose error is corrected by the constrained I2S calibration process.

2.4 Constrained Pose Generation

The rough calibration results \( R^C_i \) are refined by generating a constrained pose of the DHM. The refinement uses a previously developed optimization-based method [11] which incorporates the IMU measurements with the physical constraints between the DHM and the physical object. The optimization algorithm generates the DHM motion that minimizes the following objective function:
\[
F(X) = w_p F_P(X) + w_c F_C(X) + w_{RoM} F_{RoM}(X),
\]
where \( X = [t_p, \theta_1, \ldots, \theta_i, \ldots, \theta_N] \) is the design variables consisting of the pelvis position of the DHM, \( t_p = [x_p, y_p, z_p] \), and the roll-pitch-yaw angles of the \( i \)th joint, \( \theta_i = [\theta_{x_i}, \theta_{y_i}, \theta_{z_i}] \). The objective function \( F(X) \) is calculated as the weighted sum of the cost functions, \( F_P(X), F_C(X), \) and \( F_{RoM}(X) \). The orientation cost \( F_P(X) \) evaluates the orientation difference between the IMUs and the DHM’s body segments, and \( F_{RoM}(X) \) is the penalty function, which increases when the DHM’s joint angle exceeds its range of motion (RoM). \( F_C(X) \) constrains the DHM motion to satisfy the physical constraints \( C_k \). In the constraints \( C_k = [v_p^k, v_s^k, n_k, T_k] \), which are specified by the user, the skin vertex \( v_s^k \) and the product vertex \( v_p^k \) represent the points located on the surface mesh of the DHM and the target geometry, respectively, and \( n_k \) is a unit vector for calculating the directional distance. The constraint type \( T_k \in \{'P', 'S', 'N'\} \) represents the relation between \( v_p^k \) and \( v_s^k \), where \( 'P' \), \( 'S' \), and \( 'N' \) indicate the point-to-point contact, the point-to-surface contact, and the non-penetration, respectively. Based on \( C_k \), \( F_C(X) \) is calculated as follows:
\[
F_C(X) = \sum_{k=1}^{K} d_k^2,
\]
\[
d_k = \begin{cases} \| p(v_p^k, v_s^k) \| & (T_k = 'P'), \\ p(v_p^k, v_s^k) \cdot n_k & (T_k = 'S'), \\ g(p(v_p^k, v_s^k) \cdot n_k) & (T_k = 'N'), \end{cases}
\]
where \( K \) and \( p(v_1, v_2) \) denote the number of constraints and the position vector from \( v_1 \) to \( v_2 \), respectively. The desired motion of the DHM is automatically generated by applying the constraints on the given physical object. The number of constraints \( C_k \) is not necessarily larger than the number of design variables \( X \), because \( X \) is determined by \( F_P(X) \) and \( F_{RoM}(X) \) in addition to \( F_C(X) \). Note that \( t_p \) is set to \( [0, 0, 0] \) and removed from \( X \) when any contact constraint \( C_k \) is not specified since \( t_p \) is determined by the effect of \( F_C(X) \). This algorithm is detailed in our previous study [11],[21].

2.5 Constrained I2S Calibration

The refined calibration matrix \( R^C_i' \) is calculated by performing the I2S calibration using the generated constrained pose as the reference pose. In particular, \( R^C_i' \) is calculated by Eq. (4), replacing \( R^t_i \) of the DHM with that of the DHM in the constrained pose.

2.6 Real-Time IMU-Based MoCap

Finally, the DHM motion is estimated on the fly by the optimization algorithm described in Section 2.4. In this process, the subject movements can be estimated by the orientation, contact, and RoM constraints, which differ from those used in the constrained pose generation step. Thus, the system can estimate any movements of the subject, not only the motions similar to the reference pose in the calibration.

To validate the effectiveness of the proposed calibration algorithm, we performed the experiments without the contact constraints in Sections 3 and 4. Note that \( t_p \) is determinable if the contact constraints are applied even in the real-time motion estimation process, e.g., contact between the sole and foot pedal of the motorcycle.

3. Preliminary Experiments

3.1 Experimental Settings

In the preliminary experiment, the chair and chair-sitting were used for the constrained calibration by the proposed system. The effectiveness of the proposed system was validated by comparing the motions of the proposed constrained I2S calibration and the single standing-pose calibration. As shown in Fig. 2, 57 reflective markers were attached on the subject and tracked by 15 infrared MoCap cameras [22]. Meanwhile, 15 IMUs were attached to the subject by elastic belts [23]. Prior to measurement, the calibration poses (i.e., the standing and
chair-sitting poses) were thoroughly explained to the subject. Three young male subjects participated in the experiment, with body heights and weights of (1.62 m, 52 kg), (1.71 m, 64 kg), and (1.63 m, 100 kg). The experiment was approved by the ethical review board of the author’s institute (National Institute of Advanced Industrial Science and Technology).

3.2 Constraints for Generating Chair-Sitting Pose

To generate the constrained chair-sitting pose, as shown in Fig. 3, we introduced the following constraints.

(a) \( C_f = \{ v_f^s, v_f^p, n(v_f^p), 'S' \} (v_f^p \in V_f) \): The constraint \( C_f \) grounds the foot sole surface of the DHM on the floor surface, where \( n(v) \) represents a unit normal vector at the vertex \( v \).

(b) \( C_s = \{ v_s^p, v_s^b, m(v_s^b), 'S' \} (v_s^p \in V_s) \): \( C_s \) places the DHM on the chair seat.

(c) \( C_l = \{ v_l^p, v_l^c, m(v_l^c), 'S' \} (v_l^p \in V_l) \): \( C_l \) contacts the left hand and forearm on the left armrest.

(d) \( C_r = \{ v_r^p, v_r^b, m(v_r^b), 'S' \} (v_r^p \in V_r) \): \( C_r \) contacts the right hand and forearm on the right armrest.

(e) \( C_b = \{ v_b^p, v_b^c, m(v_b^c), 'S' \} (v_b^p \in V_b) \): \( C_b \) contacts the back and both shoulders on the seat back.

(f) \( C_c = \{ v_c^p, v_c^b, n(v_c^b), 'S' \} (v_c^p \in V_c) \): \( C_c \) ensures that the DHM’s medial plane meets the medial plane of the chair.

It further closes the gaps between both legs of the DHM.

These constraints were specified by picking the relevant points from the geometric data of the chair.

3.3 Motion Trials

As shown in Fig. 4, the following motions were measured for each subject: (1) standing, (2) sitting on the sofa, (3) sitting on the high chair, and (4) half squat. Motion (1) was measured for the rough calibration of the proposed system, i.e., single-pose calibration with standing pose. Motion (2) was measured for the proposed constrained calibration. Motions (3) and (4) were measured for validating the proposed calibration. For the validation test, the subjects were asked to sit on the high chair without any instruments. Thus, their legs were not always closed, and their heels were not always flat on the floor, as shown in

Fig. 4. Motion (3) for validation was performed on a chair. The heights of the seat \( h_s \) and armrest \( h_a \) were \( h_s = 377 \) mm and \( h_a = 586 \) mm for the sofa in the motion (2), and \( h_s = 502 \) mm and \( h_a = 696 \) mm for the chair in the motion (3). Since the downward displacement of a seat cushion of the sofa used in the motion (2) was not large (approximately 20 mm), so this deformation was ignored in the pose generation process. Note that the object used for the calibration should be rigid or less deformable for the reliable I2S calibration.

3.4 Results of Constrained Pose Generation

Figure 5 shows the results of motion (2) (i.e., sitting on the sofa) under the sitting-pose constraints. The blue-colored DHM was measured by the marker-based MoCap and used as the ground-truth data. The green-colored DHM in Fig. 5 (a) was the estimation results using the IMUs alone. As shown in the figure, the results disagreed with the actual motions, especially those of both legs. In contrast, the estimation results of the proposed system using the IMUs, the physical constraints, and the RoM (red-colored DHM in Fig. 5 (b)) well matched the actual motions. Under the imposed constraints, the estimation results were very similar to the actual pose, which was further used in the constrained I2S calibration. In these figures, the red- and green-colored DHMs were superimposed to correspond their pelvis positions to that of the blue-colored DHM for visualizing estimation errors.

3.5 Results of Real-Time Motion Estimation

Figure 6 compares the estimated motions in the single pose calibration using the standing pose (green-colored DHM) and the proposed constrained calibration using the chair-sitting pose (red-colored DHM). Figure 7 shows the joint angle errors of the lower extremities in these poses, where \( \theta_{\text{hi}x}, \theta_{\text{hi}z}, \theta_{\text{ki}x}, \theta_{\text{ki}z} \) are the angle errors of the hip joint in flexion-extension, the hip joint in abduction-adduction, the knee joint in flexion-extension, and the ankle joint in flexion-extension, respectively. In this study, all estimates and measurements were represented in the same link structure. Thus, the angle errors were simply averaged for each motion trial using the absolute values of the joint angle difference between the estimation results and the ground-truth data.

3.6 Discussion

As shown in Fig. 5 (a), the chair-sitting pose using the IMU measurements alone contained considerable errors, especially in the upper legs. Such errors originated from sensor drift in the presence of environmental magnetic disturbances [5], skin deformation artifacts caused by joint motions and the seat-body contact [6], and poor-quality calibration [7],[8]. These errors
Fig. 6 Comparison of motion estimation errors (blue: marker-based MoCap, green: calibration with standing pose, red: constrained calibration).

Fig. 7 Comparisons of the joint angle estimation errors (see text for meanings of the angles).

Fig. 5 Comparison of pose generation error (blue: measured by marker-based MoCap, green: estimated using IMUs alone, red: estimated while imposing the constraints).

were corrected by applying the physical constraints (Fig. 5 (b)). Among the constraints in Fig. 2, \( C_c \) effectively corrected the errors in both legs, closing the gap between the legs of the DHM.

Figures 7 (a)–(c) validate the sitting on the high chair. From the aspect of joint angle errors, the significant errors in the hip angles \( \theta_{Hx} \) and \( \theta_{Hz} \) in Figs. 7 (a)–(c) were also improved by the proposed calibration method. As shown in Figs. 7 (d)–(f), the proposed system was further validated by the half-squat motion, which is dissimilar to the calibration pose. The calibration procedure reduced the significant errors in \( \theta_{Hx} \) and \( \theta_{Hz} \) as well as in the sitting motion.

Although the proposed system improved the significant errors in \( \theta_{Hx} \) and \( \theta_{Hz} \), small accuracy reductions was observed in some cases, where the error in \( \theta_{Ax} \) was increased by approximately 6 degrees at maximum (Fig. 7 (c)). This is because the
The proposed method optimizes the joint angles of the DHM to satisfy the orientation, contact, and RoM constraints at the same time. Thus, depending on the orientation accuracy of each IMU and the degree of correspondences between the applied contact constraints and the actual contact, there is a possibility that the optimized angles do not always correspond to the actual values.

In addition, the improvements of hip joints seemed to be more effective than that of the ankle joints. This was due to the fact that the changes of the hip joint angle contribute to satisfying the contact constraints applied in legs, i.e., \( C_f, C_c, \) and \( C_s \).

Figure 8 shows the differences in body dimensions between the constructed DHM and the model measured by the marker-based MoCap system. In this figure, the length of leg, arm, and trunk indicate the sum of the link length from thigh to foot, upper arm to hand, and pelvis to neck, respectively. As shown in the figure, although the maximum error was less than 80 mm, the improvement of the human modeling accuracy might lead to the improvement of the accuracy of the proposed I2S calibration method. In addition, there is a possibility that the accuracy decreases as the subject volume increases due to the skin deformation artifact. For such cases, this deformation needs to be imitated in the pose estimation algorithm, e.g., applying the bias distance to \( F_C(X) \) which is determined by the subject volume.

The proposed system also enables the I2S calibration with product-use poses, i.e., poses when using products such as chairs, cars, and bicycles. As observed in the sitting motions (Figs. 7 (a)–(c)), the high estimation accuracy of the system might be explained by the constrained calibration postures, which are similar to product-use poses. To validate and demonstrate this idea, we applied the proposed system to motion estimation of riding on a motorcycle, using the motorcycle and riding pose in the proposed constrained calibration. The details are described in the following section.

4. Application to Riding-Motion Estimation

4.1 Experimental Settings

The movements of a motorcycle rider greatly affect the vehicle dynamics. Thus, measuring the rider movements can potentially level the rider skills. Rider motions are often analyzed by monitoring the center-of-mass (CoM) movements [23]. This section applies the proposed IMU-based MoCap system and the constrained I2S calibration to the measurement of the CoM movements of motorcycle riding.

The experimental setting was that of Section 3. The experimental subjects were two males with body heights and weights of (1.61 m, 66.0 kg) and (1.68 m, 55.0 kg). As shown in Fig. 9, to validate the proposed system, a motorcycle mockup was placed on the measurement area of the marker-based MoCap system. This mockup object provided the physical object for the constrained I2S calibration, with the contact constraints specified between the DHM and the motorcycle body. During the experiment, several motions (see Fig. 10) were measured by both IMU and the marker-based MoCap systems.
4.2 Constraints for Generating the Riding Pose

To generate the constrained riding pose for the I2S calibration, as shown in Fig. 11, the following constraints were imposed on the reference poses shown in Figs. 9 and 11.

(a) $C_{rfj} = \{v_{rfj}, v_{RF}, P\}$: $C_{rfj}$ places the centers of the right and left soles on the right and left foot pedals, respectively.

(b) $C_{rlh} = \{v_{rlh}, v_{RH}, LH, P\}$: $C_{rlh}$ ensures that the right and left hands grip the right and left handles, respectively.

(c) $C_{rs} = \{v_{rs}, n_{RS}, S'\}$: $C_{rs}$ is the no-penetration constraint between the hip and the seat.

(d) $C_{s} = \{v_{s}, n_{s}, S'\}$: $C_{s}$ places the DHM on the seat of the motorcycle.

(e) $C_{c} = \{v_{c}, n_{c}, S'\}$: $C_{c}$ ensures that the DHM’s medial plane meets the medial plane of the motorcycle. $n_{c}$ represents the Y-axis of the IMU sensor placed on the motorcycle, where the axis represents the left-to-right direction of the motorcycle (see Fig. 11).

For a quantitative validation, Fig. 13 compares the CoM estimation results of the proposed system with those of typical I2S calibration. The CoM was estimated more accurately in the proposed system than in the typical I2S calibration.

The product vertices in the constraints were picked from the geometric data of the motorcycle. In our previous study [21], we used such constraints when estimating the pedaling motion on a bicycle ergometer by the typical I2S (standing pose) calibration method. Here we apply these constraints in the constrained I2S calibration and omit them from the real-time motion estimation.

4.3 Results of the Riding-Motion Estimation

Figure 12 shows the results of the riding-motion estimation. The estimation results of I2S calibration with the standing pose contained significant errors (Figs. 12 (a)–(d)), which were corrected by the proposed I2S calibration algorithm (Figs. 12 (e)–(h)).
Figs. 14 and 15 evaluate the joint angles of the lower extremities and the torso angle in the sagittal plane. The angle errors were calculated as done in the preliminary experiment, and their averaged errors were shown in the figures. The torso angle was calculated and validated by the elevation angle representation in the sagittal plane, i.e., the angle between the torso and the horizontal plane. This is because some reflective markers for tracking the pelvis were not always captured by the optical MoCap system. As shown in the figures, the joint angle estimation accuracy was improved by the proposed constrained calibration method for all four-poses.

Figure 16 shows the differences in body dimensions between the constructed DHM and the model estimated by the marker-based MoCap system. The result is similar to the preliminary experiment, i.e., the maximum error was less than 80 mm.

The experimental results of this section and Section 3 verify that the proposed I2S calibration algorithm improves the motion estimation accuracy of the IMU-based MoCap system and enables I2S calibration using product-use poses.

5. Conclusions

This study introduces our constrained I2S calibration system for the IMU-based MoCap system. The constrained pose was generated by incorporating the IMU measurements with the physical constraints between the body and the physical object. In the preliminary experiment, the joint angle estimation accuracy was validated by comparing the constrained calibration using the chair-sitting poses and the standing pose. The angle errors (especially those in the hip joints) were considerably reduced by the proposed system, although a few accuracy reductions were observed in some cases. The accuracy was improved not only during chair-sitting motions resembling the calibration pose but also during half-squat motions. The proposed system was then applied to riding-motion estimation. The proposed system more accurately estimated the CoM movement and joint angles of a motorbike rider than typical I2S calibration and enabled calibration using the product-use poses.

In this study, the sofa and motorcycle were used as the object for the constrained I2S calibration. The rigid or less deformable object is desired for the reliable I2S calibration. In addition, it is desirable to use the object which contacts with human body on multiple points to constrain the human motion. Thus, the motorcycle was an ideal example. In other examples, the non-deformable chair with armrest, exercise machines such as ergometer, nursing-care equipment such as wheeled chair can be utilized for the constrained I2S calibration.

The proposed system estimates the constrained pose based on the interaction between the DHM and the product surface. Thus, the estimation accuracy is affected by the modeling ac-
curacy of the DHM. Further validation with a broader range of subjects and the integration of the recent body scanning technologies will be examined in our future work.

The proposed system enables I2S calibration with the sitting pose. Therefore, in a future study, we will also measure the transferring motions of a wheelchair’s user, which cannot be calibrated by the typical I2S method based on standing or walking motions.

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