Towards an Assistive Robot that Autonomously Performs Bed Baths for Patient Hygiene

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***Abstract*— This paper describes the design and implementation of a behavior that allows a robot with a compliant arm to perform wiping motions that are involved in bed baths. A laser-based operator-selection interface enables an operator to select an area to clean, and the robot autonomously performs a wiping motion using equilibrium point control. We evaluated the performance of the system by measuring the ability of the robot to remove an area of debris on human skin. We tested the performance of the behavior algorithm by commanding the robot to wipe off a 1-inch square area of debris placed on the surface of the upper arm, forearm, thigh, and shank of a human subject. Using image processing, we determined the hue content of the debris and used this representation to determine the percentage of debris that remained on the arm after the robot completed the task. In our experiments, the robot removed most of the debris (>96%) on four parts of the limbs. In addition, the robot performed the wiping task using relatively low force (<3 N).**

I. INTRODUCTION

It is estimated that more than 10.8 million Americans, including 2.2 million people with motor impairments, need personal assistance with activities of daily living (ADLs) [1]. In addition, the rapid increase of the older adult population, expected to reach 21 percent by 2030 in the U.S. [2], will create new challenges for our society. A significant portion of the older adult population is likely to require physical assistance with ADLs [2]. The growing population of those with disabilities will create the need for more nursing and home-care services from the healthcare industry. However, studies have shown that there is a growing shortage of nurses [3], [4], and each additional patient per nurse is associated with an increase in patient mortality by 7% [5]. Development of assistive robots would potentially relieve the workload of nurses, as well as grant more independence and a better quality of life for those who need assistance with ADLs.

Several studies have shown that people with with motor impairments ranked fetching dropped objects, performing hygiene tasks, and feeding as high priority tasks for assistive robots [6], [7], [8]. To date, researchers have focused on developing robots that can grasp or fetch objects in order to provide assistance for this population [9], [10], [11], [12].

However, there has been relatively little work on developing robots that provide hygiene assistance. ASIBOT is a teleoperated, table-mounted robotic arm and is reported to have toothbrushing capability [13]. Stanford DeVar is a voice-controlled, desktop-mounted robotic system that is capable of performing toothbrushing and shaving [8]. The

Fig. 1. **Experimental Setup:** The robot Cody was situated along side the patient bed, ready to perform the cleaning task to a subject (IRB approval and user permission obtained).

Handy 1 robot, which consisted of an arm on a wheeled cart with a specialized tray and a specialized spoon, provides assistance with eating and drinking using pre-programmed motions [14]. Efforts were also made to extend its capabilities to face shaving and cleaning, but it's not clear if this was successful and would seem to be challenging given the system's capabilities. The KARES II assistive mobile manipulator from Korea performed face shaving and wiping with a compliant arm while the base was held fixed. Few details are provided about the system's performance, but user feedback for some of the tasks in a small study (6 people with disabilities with 3 trials each) was positive. Interestingly, high compliance was preferred for shaving, while users did not like wiping because it was too compliant [15].

There are robots that actively make contact with human skin, including an oral rehabilitation robot that massages the face of a user [16], and a skincare robot that applies lotion to a user's back [17]. Previously, we have developed a teleoperated robotic system that is capable of performing a wiping task, and have demonstrated its feasibility by testing it on a mannequin [18].

We believe that a robot that can autonomously perform hygiene tasks could potentially provide benefits to people with motor impairments, including: (1) increasing privacy and comfort; (2) increasing independence and a better quality of life; and (3) providing consistent performance in long-term operation over different users. Such capabilities may also

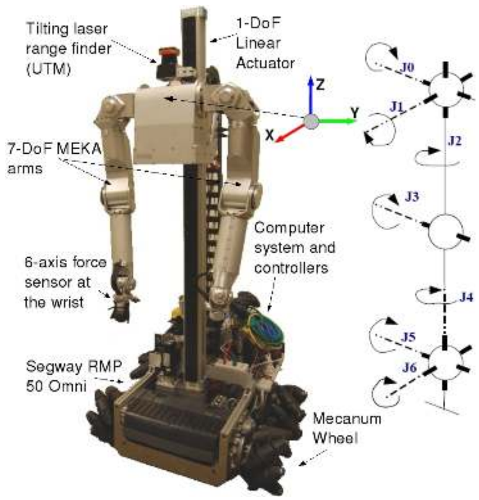

Fig. 2. **Left:** Cody, the mobile manipulator used in this paper and the coordinate frame attached to the torso. **Right:** The orientation of the 7 joint axes of each arm (copied with permission from MEKA Robotics datasheets).

benefit nurses, including: (1) reducing the workload of nurses by decreasing cognitive and physical loads; (2) freeing up time for nurses to use to perform other tasks; (3) decreasing work-related injuries for nurses.

A. *Patient bathing*

Patient bathing has been a significant part of nursing care. In fact, bathing was reported as one of the first ADLs that residents of a nursing home population lost the ability to perform [19]. Florence Nightingale (1820-1910), credited in her role of founding the modern nursing profession, discussed the necessity of providing personal cleanliness for both the patient and nurse to provide comfort, promote healing, and control the spread of infection [20]. Bathing is a hygienic practice used to remove sweat, oil, dirt, and microorganisms from the skin. Other benefits include eliminating body odor, reducing the potential for infection, stimulating circulation, providing a refreshed and relaxed feeling, improving self-image, and maintaining skin integrity [21].

There are four main types of methods that nurses and caregivers use to bathe patients, including the complete bed bath, partial bed bath, tub bath, and shower [22]. The complete bed bath is performed entirely by the nursing assistant or caretaker while the partial bed bath is performed by the nursing assistant and patient together as a team. Both types of bed baths are performed while the patient is in a bed. Tub baths and showers are taken while the patient is sitting in a bathtub or shower, respectively, with or without assistance.

To administer a bed bath, the nurse first wraps a damp washcloth around his hand to create a bath mitt. The nurse proceeds to wash (by adding soap to the bath mitt and wiping the patient), rinse (wiping the patient with a clean, moist bath mitt), and pat dry the patient's face, limbs, neck, back, and buttocks [22]. The nurse places a towel underneath each limb as he performs the washing, rinsing, and drying procedures [22]. In nursing literature, the most common method of

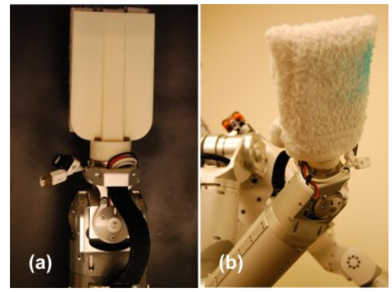

Fig. 3. **End effector design.** (a) The specialized end effector made out of ABS plastic. (b) The end effector wrapped with a towel, following how nurses wrap a towel around their hand to create a bath mitt.

evaluating the performance of bathing is to compare the microbial counts on the skin from before and after a nurse bathes a patient [23]. Experimenters collect skin specimens from each subject using sterile cotton swabs, and analyze the results of the microbial cultures of the specimens. However, nurses generally do not use such means to evaluate the quality of their cleaning on a day-to-day basis.

In this paper, we present our progress towards a robotic system that is capable of performing a cleaning task. Once the operator selects an area to clean, the robot autonomously wipes the selected area on the person's limb.

II. Implementation

A. *System Description*

In this study we used Cody, a statically stable mobile manipulator assembled at the Healthcare Robotics Lab, to perform the cleaning task (Fig. 2). It consists of arms from MEKA Robotics (MEKA A1), a Segway omni-directional base (RMP 50 Omni), and a 1 degree-of-freedom (DoF) Festo linear actuator. One of our design considerations for human-centered robotics is to use robotic arms that have actuators with low mechanical stiffness. The arms consist of two 7-DoF anthropomorphic arms with series elastic actuators (SEAs) and the wrists are equipped with 6-axis force/torque sensors (ATI Mini40).

We gather laser range data from a tilting Hokuyo UTM-30LX and images from a Point Grey Firefly camera (Fig. 4). The laser range finder and the camera are mounted atop a RX-28 Robotis servo located above the torso. Cody uses two computers running Ubuntu Linux and we have written all our software in Python.

We use equilibrium point control (EPC) [24] which is a form of impedance control inspired by the equilibrium point hypothesis for all arm motions. Using EPC, the motion of the robot's arm is commanded by adjusting the position of a Cartesian-space equilibrium point (CEP) over time. The CEP denotes where the end effector would settle in the absence of externally applied forces other than gravity. For our implementation, this is achieved through the use of virtual visco-elastic springs at the robot's joints along with gravity compensation. For any commanded CEP, we find the associated equilibrium angles for each joint of the arm that would result in the end effector settling at the CEP, except for

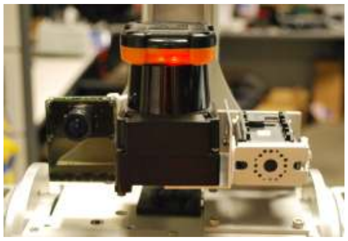

Fig. 4. Tilting laser range finder and camera mount.

two joints in the wrist (pitch and yaw). For these two joints we use position control, which relates the motor output to joint encoder values and ignores torque estimates from the deflection of the SEA springs [24]. Consequently these two joints are held stiff, except for the passive compliance of the SEA springs and cables connecting the SEAs to the joints. Even when the wrist is held stiff, the end effector still has significant compliance relative to a typical industrial arm.

We used a flat, 3D-printed, spatula-like end effector (7.8 cm x 12.5 cm, Fig. 3a) which resembles an extended human hand [18]. We wrapped a moistened towel around the end effector (Fig. 3b) to simulate the bath mitt that nurses create while performing bed baths.

B. Operator-selection of the wiping area

We have created a selection interface that allows the operator to select the area he wishes the robot to clean. First, the servo tilts the laser-range finder and the camera downward through a 45-degree arc from its original resting position shown in Fig. 4. The laser range finder captures a point cloud as it sweeps through the arc, and the camera captures one image using OpenCV at the end of the arc. The point cloud and the image are overlaid and are presented to the operator, who uses a mouse to select two points on the overlaid image. These two points are transformed to 3D Cartesian points in the robot's coordinate frame which is defined in Fig. 2. The two points form the diagonal corners of a rectangular bounding box that the operator wishes the robot to clean.

C. Wiping Behavior

After the operator selects the area, the robot autonomously executes the wiping behavior sequence (Algorithm 1) using the right arm. All variables are defined with respect to the robot's coordinate frame as shown in Fig. 2. We developed the algorithm based on the assumption that the surface normal of the cleaning area is approximately oriented with gravity (z-axis). The robot generates a CEP above the first operator-selected point in the z-axis, and then moves the CEP downward until the force in the z-direction at the wrist reaches a threshold (2 N). This allows the end effector to follow the CEP downward until making contact with subject's body (Function LOWER_UNTIL_HIT() in Algorithm 1).

The selected rectangular bounding box provides the distances ($dist_x$ and $dist_y$) and the initial directions (dir_x and dir_y) along the x-axis and y-axis that the robot will use to perform the wiping motion. The robot computes a sequence of CEPs that approximately move the CEP at 4cm/s. (Function SURFACE_FOLLOW()). The robot uses a bang-bang controller that attempts to maintain a z-axis force against the subject's body between 1 and 3 N. The CEP is updated at 20 Hz, and is adjusted 3 mm upward or downward depending on whether the force exceeds 3 N or is under 1 N.

Algorithm 1 WIPE$(pt_{init}, dir_x, dir_y, dist_x, dist_y)$

```
GoTo(pt_init + z_offset)
LOWER_UNTIL_HIT()
moves ← CEIL(dist_x/2cm)
for i = 0 to moves do
    for i = 0 to 2 do
        SURFACE_FOLLOW(arm, dir_y, dist_y)
        SURFACE_FOLLOW(arm, −dir_y, dist_y)
    end for
    SURFACE_FOLLOW(arm, dir_x, 2cm)
end for
```

The end effector approximately moves back and forth for a distance $dist_y$ starting in the direction dir_y, repeats this oscillatory wiping, and then moves for 2.0 cm in the direction dir_x. Due to low stiffness of robot's joints, the end effector can tolerate some surface curvature. The number of times that the robot repeats its move in the x- and y-direction (*moves*) is determined by the value CEIL($dist_x$ / 2.0 cm). For example, if $dist_x$ is 7.1 cm, then the robot will move in the x-direction four times and follow each of these moves with wiping parallel to the y-axis. The robot lifts its end effector off the subject's body when the behavior is completed. Fig. 5 shows a sequence of photos of the wiping behavior performed on a human subject.

D. Accuracy of the End Effector Position

We evaluated the error between the desired position of the end effector from the selection interface (Section II-B) and the resultant position of the end effector in the environment. We situated Cody in front of a table with 2 cm x 2 cm checkerboard squares. An experimenter used the selection interface to select a point on the checkerboard grid to command the robot's end effector to move to the operator-selected point using the Function LOWER_UNTIL_HIT() (Algorithm 1). We then measured the distance between the point on the checkerboard grid that the operator had selected and the actual position of the end effector (the center point along the front edge of the end effector). We conducted this test across 16 grid points over a 6 cm x 6 cm total area. The results showed that the root mean square (RMS) error is 0.62 cm on the x-axis and 0.72 cm on the y-axis.

E. Safety

Since the robot is making direct physical contact with a human, we use several safety features. First, we use a run stop button that can terminate the robot's motion during

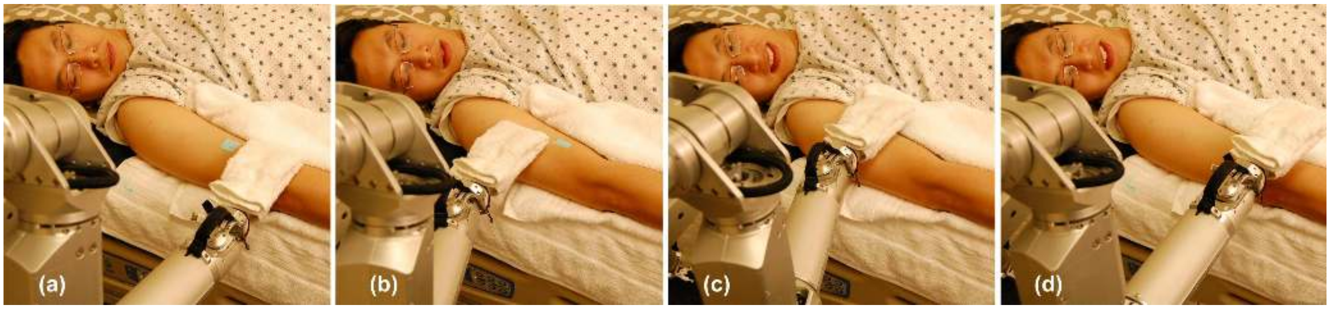

Fig. 5. **Sequence in a cleaning task:** (a) initial contact made with upper arm; (b) wiping to the left; (c) wiping to the right; (d) task completed.

the experiment. The experimenter can push the button to stop the robot's motion in the event that it may make undesirable contact with the subject. Second, low stiffness of the robot's joints may soften the impact with the subject (see Section II-A). Third, the robot's controller (Section II-C) attempts to maintain the downward (z-axis) force against the subject's body to be lower than 3 N. In comparison, Tsumaki et al. reported that subjects experienced no pain when a skincare robot applied 10 N in the z-direction [17]. Lastly, we command the robot to stop if the magnitude of the total force measured by the wrist's force-torque sensor exceeds 30.0N, which is within the force limit of 39.2 N used by an oral rehabilitation robot [16].

III. Experiment

We performed the cleaning task on a lab member who laid on a fully functional Hill-Rom 1000 patient bed (Fig. 1). Cody was situated at the side of the bed facing the subject, and it remained stationary throughout the experiment. The operator set up the experiment following the procedure of a standard bed bath [22]: adjust the bed to a flat position; lower the side rail; ask the subject to move to the side of the bed that is closer to Cody (Fig. 1); and place the subject's limb on a towel to soak up any water dripping from the washcloth. Studies have shown that patients feel the least awkward when nurses touch their limbs versus other body parts [25]. For this reason, we performed the cleaning task on four segments of the subject's limbs: the upper arm, forearm, thigh, and shank. In this paper, we refer to the segment of the upper limb between the shoulder and the elbow as the upper arm, and between the elbow and the wrist as the forearm. Also, we refer to the segment of the lower limb between the hip and knee as the thigh, and between the knee and ankle as the shank.

The operator placed a 1-inch square quantity of debris in the form of blue Pixy Stix (Nestle S.A., Switzerland), a powdered candy with blue food coloring, on the surface of the limbs (Fig. 6). The robot performed the cleaning task autonomously to wipe off the square of debris. The reasons for selecting the blue powdered candy were: (1) The square of powdered candy simulates an area of accumulated debris on the human body; (2) food coloring and powdered sugar are highly biocompatible with human skin; (3) blue is distinctly different from the color of human skin, thus enabling us to easily quantify the success rates of debris removal; and (4) the substance hardly leaves stains on the skin after it is wiped off. These properties make it easier to analyze the cleaning performance using image processing methods.

The operator initiated an autonomous cleaning task by first selecting the bounding box to enclose the debris, and then initiating the wiping behavior. The subject was asked to be stationary during the test, and the operator informed him before the robot initiated the task. Using a tripod-mounted camera, we took a picture of the limb segment with the debris *before* the cleaning task, and then once again *after* the robot performed the cleaning task. We also recorded the forces and torques experienced at the end effector during the task. At the conclusion of the testing, the experimenter debriefed the subject about his experience of the test.

We evaluated the performance of the wiping behavior by considering the ability of the robot to remove the debris. To do this, we used Matlab and its Image Processing Toolbox to convert the *before* and *after* images into the HSV space.

In order to model the color of the debris, first we manually selected a polygonal region that outlined the debris in the before image. We then computed the mean hue in this region. For this experiment, we consider any pixel with a hue value less than three standard deviations away from this quantity to be debris. We then increased the area of the polygonal region by three times and used it to count the number of debris pixels in the after image. Finally we divided the number of debris pixels in the after image by the number of debris pixels in the before image to obtain a percentage.

IV. Results

The results of the cleaning trials are shown in Table I. We expect the areas of the bounding box to be varied because each box was manually selected, and for the completion time to be proportional to the area that the end effector has traveled.

Across all trials there was only a small portion of the debris left on the limbs (<3.05%). The upper arm trial had the highest percentage of remaining debris (3.05%), followed by the shank trial (2.08%), while both the forearm and thigh trials had no remaining debris (0.0%). The mean force magnitude in all directions of all trials was relatively low (<3.1 N). The mean of force |Fz| for each trial was lower than the 3

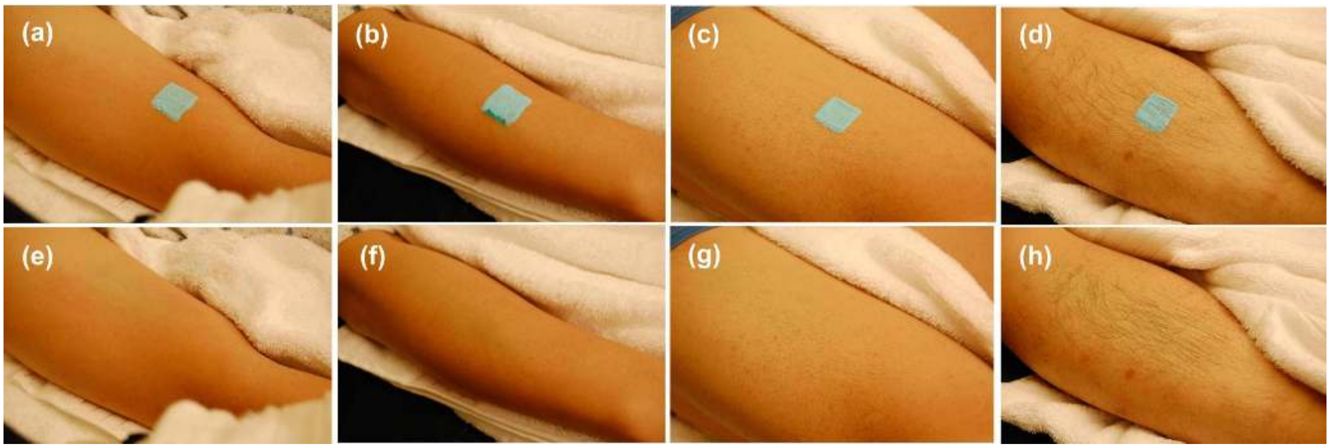

Fig. 6. **Images of the limbs *before* and *after* the cleaning task:** (a) *before* image of the upper arm; (b) *before* image of the forearm; (c) *before* image of the thigh; (d) *before* image of the shank; (e) *after* image of the upper arm; (f) *after* image of the forearm; (g) *after* image of the thigh; and (h) *after* image of the shank.

N maximum force limit in the SURFACE_FOLLOW() function used in Algorithm 1 and these forces were approximately equal to the minimal force (1 N) in the same function. Given the large standard deviation values of |Fz| for all trials (0.9 N - 1.1 N), the robot arm may have gone below the force threshold many times and then corrected itself by creating a new CEP in the negative z-direction.

V. DISCUSSION AND CONCLUSION

In this study we designed a behavior for a robot to perform autonomous wiping and an operator-selection interface that allows an operator to select the desired area for the robot to clean. In our experiments, the robot cleaned most of the debris (>96%) from the upper arm, the forearm, the thigh, and the shank of the human subject. This is a first step towards developing a robot that can actively and autonomously perform bed baths for patient hygiene.

In the upper arm trial, the robot wiped off most of the debris, but some staining occurred on the skin of the upper arm. This is possibly due to the moistening of the food coloring by the wet bath mitt, and it is likely that these stained pixels were counted toward the (3.08%) dirty pixels during image processing. We used a form of powdered candy to evaluate the feasibility of our robotic cleaning system. The performance may vary with different debris materials.

Using low mechanical stiffness and equilibrium point control, the wiping behavior applied relatively low forces in all trials (mean < 3.0N). Low stiffness of the robot's joints provides some tolerance to the surface contour of subject's body. However, the current implementation only allows the robot to clean areas with a surface normal approximately oriented with gravity. In order for a robot to clean all parts of the human body, it may need to actively change the orientation of the end effector to adapt to the change in surface contour. Thus, in the future we may design a robot that can clean areas with various surface normal orientations. In addition, we may also explore the implementation of bimanual cleaning tasks in which one of the robot's arms lifts the limbs of a human and the other arm cleans the surface of the limb.

Patient bed bathing is a very personal and potentially awkward task for many patients. It would be useful to conduct future work on determining potential barriers for patient acceptance of robots that perform this task. In addition, it would be useful to conduct a needs assessment of the types of patients who would receive bed baths as well as nurses who routinely administer them. In this way, we could design features that may alleviate the awkwardness of performing robotic bed baths for the patients in addition to focusing on the technical aspects of bathing. For example, to reduce the awkwardness or embarrasement that patients may feel exposing their bare skin, we may need to enable the robot to partially cover the body and only reveal the area that needs to be cleaned.

In this robotic cleaning task, the robot initiates and actively makes contact with the human. However, current research on human-robot contact has remained largely initiated by humans, not by robots [26]. The psychological impact of robot-initiated contact may become important for future human-robot interaction (HRI) research.

The subject in this study was the first author of this paper.

TABLE I
RESULTS OF CLEANING TRIALS

	Upper Arm	Forearm	Thigh	Shank
Dirty %	3.05	0.0	0.0	2.08
Mean |Fx| (N) mean (stddev)	2.0 (0.6)	2.4 (0.8)	2.0 (0.8)	2.0 (0.8)
Mean |Fy| (N) mean (stddev)	2.9 (1.6)	2.8 (1.8)	3.1 (1.7)	2.8 (1.4)
Mean |Fz| (N) mean (stddev)	0.9 (0.9)	0.9 (1.1)	1.0 (0.9)	1.3 (1.0)
Time to Complete (sec)	89.1	65.0	108.2	79.2
Bounding Box Area (cm^2)	133.9	92.4	158.4	103.2

During the debriefing, he indicated that he felt threatened by the robot touching him in the beginning of the experiment. As the experiment progressed, he felt less and less threatened by the robot and began to trust it more. At the end of the experiment, he did not feel threatened by the robot. He also indicated the force that the robot applied was comfortable throughout the experiment, and experienced no discomfort during the wiping motion in all trials. These comments suggest that repetition of positive experiences involving robot-initiated touch may enhance a human's trust toward the robot.

However, it is not known how the general population, specifically patients, would react to a robot touching them. If a nursing assistant robot were to perform a patient bathing task, then the robot would need to physically contact the patient in some manner. Thus, more HRI studies are needed on robot-initiated contact to allow researchers to design effective robots to perform some of the duties that nurses or caregivers perform.

Future work may include investigation of HRI in the context of robot-initiated contact, development of a fully autonomous system that incorporates segmentation and recognition of various body parts, evaluating user preference and task performance between autonomy and teleoperation, evaluating the behavior of cleaning of other areas of the body, and implementation for other hygiene related tasks.

VI. ACKNOWLEDGMENTS

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