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Evaluating the task effectiveness and user satisfaction with different operation modes of an assistive bathing robot in older adults

Christian Werner [a,b], Athanasios C. Dometios [c], Costas S. Tzafestas [c], Petros Maragos [c], Jürgen M. Bauer [a,b], and Klaus Hauer [b]

[a]Center for Geriatric Medicine, Heidelberg University, Heidelberg, Germany; [b]Agaplesion Bethanien Hospital Heidelberg, Geriatric Center at the Heidelberg University, Heidelberg, Germany;; [c]School of Electrical and Computer Engineering, National Technical University of Athens, Athens, Greece

ABSTRACT

Bathing robots have the potential to foster the independence of older adults who require assistance with bathing. Making human-robot interaction (HRI) for older persons as easy, effective, and user-satisfying as possible is, however, a major challenge in the development of such robots. The study aimed to evaluate the effectiveness (coverage, step effectiveness) and user satisfaction (After-Scenario Questionnaire, ASQ) with three operation modes (autonomous operation, shared control, tele-manipulation) for the HRI with a bathing robot in potential users. Twenty-five older adults who require bathing assistance tested these operation modes in a water rinsing task for the upper back. Autonomous operation led to maximum effectiveness (100%), which was significantly worse in the shared control (51.6–79.4%, $p \leq 0.001$) and tele-manipulation mode (43.9–64.4%, $p < .001$). In the user-controlled modes, effectiveness decreased with decreasing robot assistance (shared control: 51.6–79.4% vs. tele-manipulation: 43.9–64.4%, $p = 0.009–0.016$). User satisfaction with the autonomous operation (ASQ: 2.0 ± 1.0pt.) was higher than with the tele-manipulation mode (ASQ: 3.0 ± 1.4pt., $p = 0.003$) and in trend also than with the shared control mode (ASQ: 2.5 ± 1.5pt., $p = 0.071$). Our study suggests that for an effective and highly satisfying HRI with a bathing robot in older users, operation modes with high robot autonomy requiring a minimum of user input seem to be necessary.

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Activities of daily living; aged; baths; human-robot interaction; robotics

Introduction

Limitations in activities of daily living (ADLs) increase with age (Chatterji et al., 2015) and are significant predictors of loss of independence, lower quality of life, and mortality (Luppa et al., 2010; Lyu & Wolinsky, 2017; T. M. Gill, Allore et al., 2006; Manton, 1988; Rozzini et al., 2007). Among ADL limitations, those in bathing activities are among the first to occur during the aging process (Jagger et al., 2001; Katz et al., 1963) and have even been identified as a seminal point in the disabling process for older adults (T. M. Gill, Allore et al., 2006; T. M. Gill, Guo et al., 2006). Bathing is important for maintaining an individual's skin integrity and personal hygiene, thus reducing also the potential for infections and disease (Lawton, 2007; Vollman, 2013). It also serves the social purpose of eliminating body odor and maintaining an acceptable standard of cleanliness for social interactions (Ahluwalia et al., 2010; Sheppard & Brenner, 2000). Bathing represents one of the most complex ADLs (Gerrard, 2013) for which older adults require personal assistance more frequently than for other ADLs (dressing, transferring, toileting, eating) (Wiener et al., 1990). Prevalence rates for bathing disability (defined as the need for personal assistance) in community-dwelling older adults have been reported to increase with age from 4.6% to 8.6% in those ≥65 years (Wiener et al., 1990) to 21.0% in those ≥85 years (Dawson et al., 1987). In institutionalized settings such as nursing homes or personal care facilities, an even much higher prevalence rate of bathing disability (≥90%) has been documented (Jones et al., 2009; Wiener et al., 1990). The demographic change toward an aging society will further increase the number of older adults in need for bathing assistance, and thus also the burden on the formal and informal care system. As bathing is one of the most sensitive and intimate ADLs, some older adults might wish to be independent from personal assistance in bathing as long as possible (Ahluwalia et al., 2010). In addition, the bathing of older people or people with a disability can be a time-consuming and physically and psychologically demanding task for caregivers (Beer et al., 2011; Kawahara et al., 2010; Yamamoto et al., 2012). A person's dependency on bathing and the caregiver burden in providing bathing assistance might be reduced through the use of assistive devices, such as grab bars, shower seats, bath chairs, and nonskid mats. However, these bath aids do not support the entire sequence of bathing tasks (i.e., bathing transfer, water rinsing, soaping, scrubbing, drying) and thus may often fail to enable users to independently complete the entire bathing process (Agree & Freedman, 2000; Ma et al., 2007). Furthermore, the evidence on the effectiveness of bath aids is still unclear (Golding-Day et al., 2017; T. M. Gill et al., 2007). In this context, assistive bathing robots that can support older adults in several bathing

CONTACT Christian Werner christian.werner@bethanien-heidelberg.de Rohrbacher Str. 149, 69126 Heidelberg, Germany
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subtasks have been proposed (Beedholm et al., 2015; King et al., 2010). Such assistive bathing robots could help to preserve independence and privacy of older adults, but also reduce the burden of caregivers in providing bathing assistance and allow them to spend more time on other care tasks and the interpersonal relationship with a care recipient, which could increase their overall productivity and quality of care.

A crucial challenge in the successful development and application of assistive robots in older adults lies in how to make interaction with the robot as easy, safe, and efficient as possible for this user group (Ka et al., 2015), in which low technology experience and negative attitudes toward robot assistance is not uncommon (Dyck & Smither, 1994; Scopelliti et al., 2004). Depending on the mode of operation, various cognitive abilities (e.g., attention, working memory, information processing) can be relevant for the human-robot interaction (HRI) with the assistive robot. Most of these cognitive abilities, however, show a pronounced decline across the life span into old age (Craik & Salthouse, 2008; Harada et al., 2013), and cognitive impairment is frequently observed in older adults with ADL limitations (Gure et al., 2013; Hakkinen et al., 2007). If the operation of the assistive robot is cognitively too demanding and too difficult to learn or use, the HRI will not be effective and the assistive robot will not be successful in accomplishing the task(s) for which it was developed (Chung et al., 2013). In addition, the users' perception of their own overload in operating the assistive robot may reduce the self-efficacy and reinforce the feeling of loss of control, which in turn may significantly affect the acceptance of and satisfaction with the robot (Hauer, 2018; Tacken et al., 2005). For developing and implementing well-accepted, easy-to-use, and effective operation modes for an assistive robot in older adults, it is, therefore, crucial to involve their feedback early in the robot design and evaluation process. Furthermore, older adults can be seen as the most heterogeneous population regarding physical, cognitive, sociological, and psychological characteristics (Hunter et al., 2016; Nelson & Dannefer, 1992; Yang & Lee, 2010), potentially also leading to a large heterogeneity in their needs and preferences for robot assistance and control. Considering personal characteristics when studying HRI has therefore been strongly recommended in older adults (Zafrani & Nimrod, 2018).

A potential approach to overcome the challenges of HRI in older adults is to reduce their cognitive load when interacting with the assistive robot by increasing its autonomy. Depending on the level of robot autonomy, operation modes of an assistive robot can be roughly categorized into (1) tele-manipulation, in which the user has full control over the robot to complete a specific task; (2) shared control, in which a synergetic collaboration between the user and the robot exists to complete the task, and (3) autonomous operation, in which the robot fully autonomously completes the task with the user only selecting the task to be executed (Abbink & Mulder, 2010; Amirshirzad et al., 2016; Schirner et al., 2013; Vogel et al., 2015; Yanco & Drury, 2004). Having in mind these different levels of robot autonomy, it is reasonable to expect that different operation modes will have an effect on the task effectiveness and the user satisfaction with the assistive robot. No comparative studies between different operation modes within the research field of assistive bathing robots in older adults have been published. Previous studies with other assistive robots (e.g., telemedicine robot, robotic walker, robotic wheelchair) suggest that task effectiveness increases with increasing robot autonomy in young or older adults with physical impairments (Erdogan & Argall, 2017; Kim et al., 2012; Koceska et al., 2019; Werner et al., 2018; Yu et al., 2003). The most autonomous operation modes with the highest task effectiveness were not those with the highest user satisfaction, suggesting that users seem to prefer to retain as much control as possible when interacting with an assistive robot (Cooper et al., 2012; Kim et al., 2012; Yu et al., 2003)

In summary, the primary aim of this study was to evaluate the task effectiveness and user satisfaction of older persons with different operation modes (autonomous operation, shared control, telemanipulation) for a water rinsing task with a bathing robot. Based on previous studies with other assistive robots, it was hypothesized that (1) task effectiveness with the bathing robot would be highest in the autonomous operation mode and would gradually decrease with lower levels of robot assistance, and (2) user satisfaction would be lower in the autonomous operation mode than in the more user-controlled operation modes (shared control, telemanipulation). A secondary aim was to explore whether there were interaction effects between the personal characteristics of the participants and the different operation modes on the user satisfaction.

Methods

I-SUPPORT bathing robot and potential users

The bathing robot used in this study was developed in the I-SUPPORT project (ICT-Supported bath robots), which aimed to develop an information and communication technology (ICT)-supported domestic service robot that assists frail older people or people with a disability in various bathing tasks (e.g., water rinsing, soaping, scrubbing, drying) (http://www.i-support-project.eu/). In brief, the I-SUPPORT bathing robot consists of a motorized chair for supporting stand-to-sit and sit-to-stand transfers and the transition into and out of the shower area, a robotic soft-arm for the specific bathing tasks (e.g., water rinsing, soaping, scrubbing, drying), Kinect V2 RGB-D sensors and condenser microphones for natural audio-gestural HRI (human and robot pose estimation, command, and action recognition), and a context-aware system for monitoring environmental (water flow and temperature, air temperature, humidity, and illumination sensors) and user information (smartwatch for user identification and (in-) activity tracking). Further technical details about the I-SUPPORT bathing robot have been published elsewhere (Zlatintsi et al., 2020). For this study, the I-SUPPORT bathing robot was installed in a typical bathroom of a rehabilitation clinic at a German geriatric hospital (Figure 1).

Potential users of the I-SUPPORT bathing robot are persons with (1) dependence in bathing activities, as defined by a score of 0 points (= person can use a bathtub, a shower, or take a complete sponge bath only with assistance or supervision from another person) for the bathing item of the Barthel Index (BI) (Mahoney & Barthel, 1965), and (2) no severe cognitive impairment, as defined by a Mini-Mental

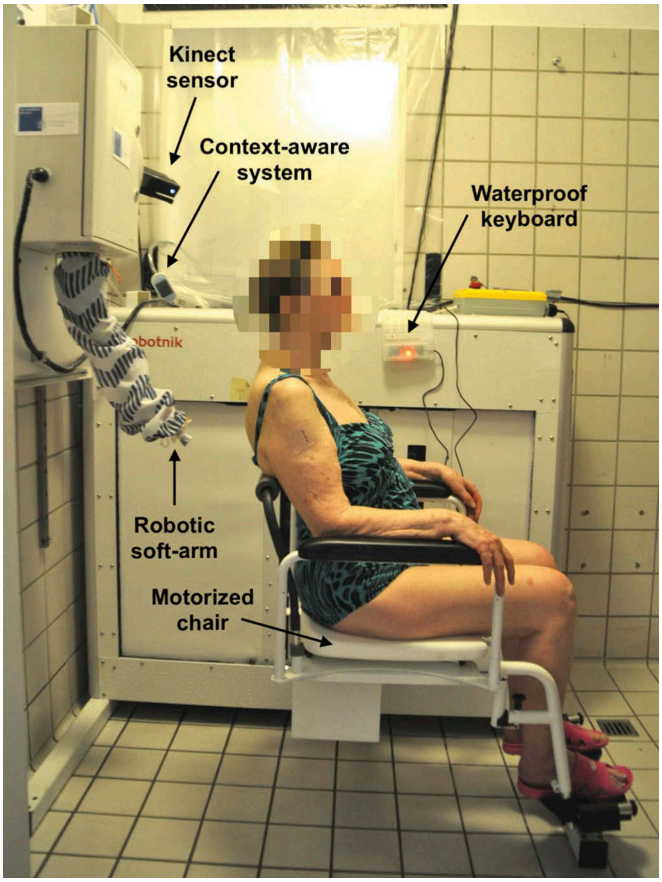

Figure 1. Installation of the I-SUPPORT bathing robot in a typical bathroom of a rehabilitation clinic at a geriatric hospital.

Figure 2. Robotic soft-arm providing water rinsing on the upper back region.

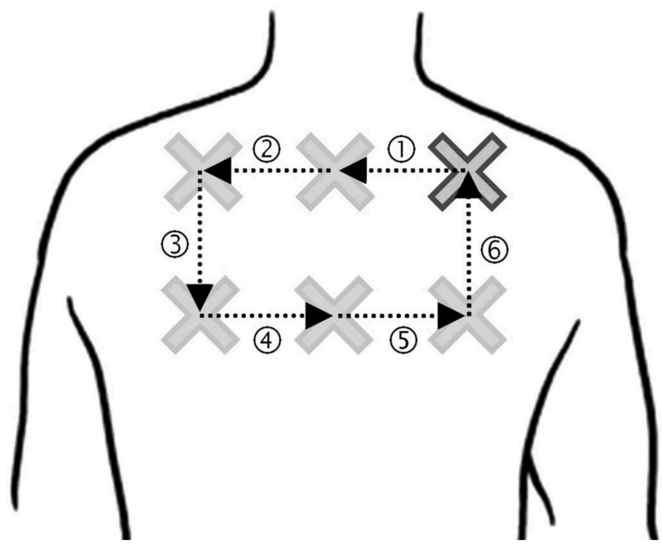

Figure 3. Upper back region with the six target points for which the soft-arm provided water rinsing. The dark gray outlined cross represents the starting and final position for all operation modes, the dotted arrows indicate the optimal 6-step path for the water-rinsing process on the upper back region.

State Examination (MMSE) score of >17 points (Folstein et al., 1975).

Operation modes of the I-SUPPORT bathing robot

The use case scenario to be evaluated in this study included the water rinsing process of the robotic soft-arm for the user's upper back region (Figure 2) as defined by six target points (Figure 3) with three different operation modes: (1) autonomous operation, (2) shared control and (3) tele-manipulation mode.

In the *autonomous operation mode*, the soft-arm of the I-SUPPORT bathing robot provides water rinsing fully automatically for a predefined body area (= upper back region) within a predefined time period and the user has no control over the motion of the soft-arm after starting the robot. The autonomous soft-arm motion in this operation mode was based on a real-time end-effector motion behavior planning method, which has previously been described in detail (Dometios et al., 2017).

In the *shared control mode*, the user issues simple motion commands for the soft-arm (i.e., one step left vs. right, up vs. down) using the arrow keys of a commercial waterproof computer keyboard, while the I-SUPPORT bathing robot provides audio assistance via beep signals. These signals indicate that (1) the specific user command is registered and (2) the motion of the soft-arm has been successfully executed according to the registered user command, meaning that the user can now issue the next motion command for the soft-arm. Further assistance in the shared control mode is provided by restricting the motion of the soft-arm to the predefined body area (i.e., upper back region cannot be exceeded). Thus, in this mode, the user has predominant, but not full control over the motion of the soft-arm.

In the *telemanipulation mode*, the user issues the motion commands for the soft-arm also using the arrow keys of the commercial waterproof computer keyboard. In this mode, however, no audio assistance for command registration and execution is provided, nor is the motion of the soft-arm restricted to the predefined body area. Consequently, the user has full control over the motion of the soft-arm.

Study design

A within-subject design was used to evaluate differences in the task effectiveness and user satisfaction with the different operation modes of the I-SUPPORT bathing robot. A mixed between- and within-subject design was used to explore the interaction effects between dichotomized participant characteristics (= between-subject factor) and the different operation modes (= within-subject factor) on the user satisfaction. The study was approved by the ethics committee of the Medical Faculty of the Heidelberg University on September 27, 2016 (S-382/2016) and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants.

Study population

Participants were recruited from rehabilitation wards of a German geriatric hospital, from nursing homes, and from a hospital-associated geriatric rehabilitation sports club. According to the user group definition of the I-SUPPORT bathing robot, only persons with dependence in bathing activities (BI bathing item = 0 pt.) and no severe cognitive impairment (MMSE score >17 pt.) were included. Further inclusion criteria were as follows: no severe ADL impairment (BI ≥ 50 pt.); independence in bed-chair transfer (BI transfer item = 15 pt.); no severe neurological, cardiovascular, metabolic, or psychiatric disorders; residence within 15 km of the study center, and written informed consent.

Test procedure

Initially, the participant wearing swimming clothes was seated on the motorized chair with the back toward the robotic soft-arm (see Figure 2) and the water temperature was set to his/her preferences. Subsequently, the test administrator explained to the participant that three different operation modes will be tested in the following order: (1) autonomous operation, (2) shared control, and (3) tele-manipulation mode.

For the first, autonomous operation mode, the participant was informed that the soft-arm will provide water fully automatically for 1 min following a 6-step path on the upper back with the starting and endpoint at the top right of the upper body (see Figure 3). To illustrate the movement path of the water stream to the participant, the test administrator showed a poster that indicated the six target points on the upper back region.

After the water rinsing task with the autonomous operation mode was completed, the test administrator explained that in the next, shared control mode, the participant must control the motion of the soft-arm by his-/herself using the arrow keys of the waterproof computer keyboard, which was placed on the thighs such that the soft-arm motion related to the direction of the arrow keys. In addition, the participant was told that the I-SUPPORT bathing robot provides some audio assistance as described above (command registration and execution) and that the motion of the soft-arm is restricted to the upper back region. The test administrator then instructed the participant to cover the entire upper back region (i.e., all six target points shown on the poster) with water and that 2 min would be provided to complete the task with the shared control mode.

Finally, the participants were told to use the tele-manipulation mode to cover the entire upper back region with water. The test administrator explained that in this mode, the soft-arm motion is also controlled by the arrow keys of the waterproof computer keyboard placed on the participant's thighs; however, the I-SUPPORT bathing robot does not provide any audio assistance for command registration and execution, nor does it restrict the motion of the soft-arm to the upper back region. Also, for this mode, each participant was informed that 2 min would be provided to complete the task.

Between testing each operation mode, a sufficient rest period was provided based on the feedback from the participant. For both user-controlled modes (shared control, tele-manipulation), the test administrator interrupted the test procedure either after the participant had successfully provided water for the entire upper back region (i.e., all six target points) or after 2 min even if the participant was not successful in water rinsing for the entire upper back region. The longer maximum processing time of 2 min in the user-control modes was chosen as for command issuing by the user and command recognition by the I-SUPPORT robot automatically more time is required than in the autonomous operation mode, in which the motion of the robotic soft-arm on the movement path is fully automatically controlled in smooth and constantly progressive way.

Descriptive measures

Demographic and clinical characteristics including age, gender, living situation (community-dwelling vs. institutionalized), falls in the previous year, and ADL status (BI) were documented by patient charts or by standardized interview. A trained interviewer assessed cognitive status (MMSE), depressive symptoms (15-item Geriatric Depression Scale, GDS-15, Gauggel & Birkner, 1999; Sheikh & Yesavage, 1986), fear of falling (Falls Efficacy Scale-International, FES-I, Dias et al., 2006; Hauer et al., 2010), technology acceptance (Senior Technology Acceptance Model, STAM, with subscales for attitude toward technology, perceived usefulness, ease of use, gerontechnology self-efficacy, gerontechnology anxiety, and facilitating conditions, Chen & Chan, 2014), and more specific bathing disabilities (e.g., ability to stand in the shower, to wash different body parts, and to dry oneself after showering/bathing) using a self-designed questionnaire. Physical performance was measured by the Short Physical Performance Battery (SPPB, Guralnik et al., 1994).

Outcome measures

Task effectiveness

The effectiveness in rinsing water on the upper back region with the different operation modes was assessed by the following two outcome parameters: (1) coverage [%], defined as the percentage of the predefined upper back region covered with water (e.g., 4 out of 6 target points covered with water = 66.7%) during the standardized time period (autonomous operation mode = 1 min, shared control and tele-manipulation mode = 2 min) and (2) step effectiveness [%], calculated as [(coverage / number of steps required) / (maximum possible coverage / minimum a possible number of steps required for maximum possible coverage)] × 100. The number of target points covered with water and the number of the steps performed during the standardized time periods were objectively calculated from the visual data obtained from the system's cameras and the kinematics combined with the behavioral-based motion controller of the robotic soft-arm of the I-SUPPORT bathing robot (Dometios et al., 2017).

User satisfaction

The After-Scenario Questionnaire (ASQ, Lewis, 1995) was used to assess the user satisfaction with the three different operation modes. The questionnaire contains three statements that address the ease of completing the task, the time taken to complete the task, and the support available when completing the task. For each operation mode, the participants were asked to rate their level of agreement or disagreement on a 7-point scale, with lower scores indicating agreement (1 pt. = strongly agree) and higher scores indicating disagreement (7 pt. = strongly disagree). The scores for the three statements were averaged into a total ASQ score. The lower the ASQ score, the higher the participants' satisfaction with the operation mode.

Statistical analysis

Descriptive data were presented as frequencies and percentages for categorical variables, and medians and ranges or means and standard deviations (SD) for continuous variables. To identify differences in task effectiveness between the operation modes, we calculated Friedman analyses of variance (ANOVAs) with post hoc Wilcoxon signed-rank tests for paired comparisons. These non-parametric tests were used due to the non-normal data distribution of the effectiveness outcomes measures. A one-way repeated-measures (RM) ANOVA with post hoc paired-samples *t*-tests was performed to test for differences in the user satisfaction between the operation modes. To explore whether there was an interaction effect between participant characteristics (age, cognitive status, functional status, physical performance, fall history, fear of falling, and technology acceptance) and the different operation modes, participant characteristics were dichotomized into clinically recognizable subgroups or two subgroups of similar sample size using a median split as follows: age (<80 years vs. ≥80 years, Baltes & Smith, 1999; Iwarsson et al., 2004), cognitive status (cognitively impaired: MMSE ≤ 26 pt. vs. not cognitively impaired: MMSE > 26 pt., Monsch et al., 1995; O'Bryant et al., 2008; Toglia et al., 2011), functional status (high: BI >85 pt. vs. low: BI ≤ 85 pt.), physical performance (low: SPPB ≤ 6 pt. vs. high: SPPB > 6 pt., Pavasini et al., 2016; Vasunilashorn et al., 2009; Veronese et al., 2014), fall history (non-fallers vs. fallers), fear of falling (low: FES-I ≤ 22 pt. vs. high: FES-I > 22 pt., Delbaere et al., 2010), and technology acceptance (STAM total score, low <60% vs. high: ≥60%). The STAM total score was defined as the mean of the percentage scores on the STAM subscales, which was each calculated as the score given for the subscale divided by the maximum possible score on the respective subscale multiplied by 100. Two-way RM-ANOVAs were used to examine the interaction effect of subgroups (= between-subject factor) by operation mode (within-subject factor = autonomous operation vs. shared control vs. tele-manipulation) on the user satisfaction. Effect sizes were calculated as r (= $Z/\sqrt{N}$) for Wilcoxon signed-rank tests ($r < 0.1$ = trivial, $0.1 \leq r < 0.3$ = small, $0.3 \leq r < 0.5$ = moderate, $r \geq 0.5$ = large effect), Cohen's d for paired-samples *t*-tests ($d < 0.2$ = trivial, $0.2 \leq d < 0.5$ = small, $0.5 \leq d < 0.8$ = moderate, $d \geq 0.8$ = large effect), and partial eta squared (η_p^2) for RM-ANOVAs ($\eta_p^2 < 0.06$ = small, $0.06 \geq \eta_p^2 < 0.14$ = moderate, $\eta_p^2 \geq 0.14$ = large effect) (Cohen, 1988). A two-sided *p*-value of < 0.05 indicated statistical significance. Statistical analysis was performed using IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY, USA).

Results

Participant characteristics

Twenty-five older persons (females: n = 20, 80.0%) who all were dependent on personal assistance or supervision in bathing activities (BI, bathing item = 0 pt.) participated in the study. Bathing disabilities most frequently reported were inability to stand independently in the shower (52%), inability to dry oneself after showering/bathing (40%), and inability to wash the back (48%), hair (32%) or feet (28%) without personal assistance. The participants' mean age was 77.9 ± 7.9 years and the MMSE score averaged 25.6 ± 3.1 points, with about half of the participants (n = 13, 52%) having some cognitive impairment (MMSE ≤ 26 pt.). The sample population showed an impaired ADL status (median BI score = 85 [50–95] pt.) and low physical performance (SPPB score = 6.1 ± 2.9 pt.). Fourteen participants (56%) reported at least one fall in the previous year. Clinically relevant depressive symptoms (GDS-15 > 5 pt.) were observed in only three participants (12%). Fear of falling was low (FES-I ≤ 22 pt.) in seven (18%) and high (FES-I > 22 pt.) in 18 (72%) participants. More than two-thirds of the participants (n = 18, 72%) reported concerns about falling while taking a shower or bath (FES-I, bathing item > 1 pt.). Technology acceptance was fair to good, with mean scores on the different STAM subscales in the upper half of the scoring range (Table 1). Eighteen participants (72%) were living at home, partly with supportive care; seven (28%) were institutionalized.

Due to technical problems with the I-SUPPORT bathing robot in three participants, the test procedure with the bathing robot could be successfully performed with only 22 participants. Additionally, technical data during the test procedure was not properly recorded in one participant; however, data on the user satisfaction in this participant was still available. No significant differences in any descriptive variables were found between the dropouts and the participants with complete data (p = 0.158–0.922).

Task effectiveness with different operation modes

In the autonomous operation mode, maximum coverage of the upper back region and maximum step effectiveness were achieved for all participants. Task effectiveness was substantially lower in the shared control and tele-manipulation modes than in the autonomous operation mode (Table 2). Only seven participants (33.3%) in the shared control mode and two participants (9.5%) in the tele-manipulation mode achieved the maximum possible coverage. Friedman ANOVAs revealed a significant effect of the operation mode on the coverage and step effectiveness

Table 1. Participant characteristics.

Variables	n = 25
Age, years	77.9 ± 7.9
Sex, females	20 (80.0)
Mini-Mental State Examination, score	25.6 ± 3.1
Barthel Index	85 [50–95]
Short Physical Performance Battery, score	6.1 ± 2.9
Recent history of falls	14 (56.0)
Geriatric Depression Scale, score	2 [0–11]
Falls Efficacy Scale-International, score	28.8 ± 10.0
Technology acceptance, score[a]	
Attitudes toward technology (max. 20 pt.)	14.6 ± 5.0
Perceived usefulness (max. 30 pt.)	19.9 ± 8.4
Ease of use (max. 20 pt.)	10.8 ± 5.0
Gerontechnology self-efficacy (max. 20 pt.)	12.2 ± 5.2
Gerontechnology anxiety (max. 20 pt.)	12.5 ± 6.1
Facilitating conditions (max. 50 pt.)	30.3 ± 10.5
Living situation	
Community-dwelling	18 (72.0)
Institutionalized	7 (28.0)

Data presented as mean ± SD, n (%), and median [range]. [a]Higher scores indicates better attitudes toward technology, higher perceived usefulness, greater ease of use, higher gerontechnology self-efficacy, lower gerontechnology anxiety, and more facilitating conditions.

($p < 0.001$). Post-hoc comparisons showed that task effectiveness was significantly lower in the shared control and tele-manipulation modes than in the autonomous operation mode, with large effect sizes ($p \le 0.001$, r= 0.74–0.84). Among the two user-controlled modes, the coverage (p = 0.009) and step effectiveness (p = 0.016) were significantly higher in the shared control than in the tele-manipulation mode, with also large effect sizes (r= 0.53–0.57).

User satisfaction with different operation modes

In general, the user satisfaction with all operation modes was positive, as indicated by mean ASQ scores in the lower quartile (autonomous operation, shared control) or lower half (tele-manipulation) of the scoring range (Table 3). RM-ANOVA revealed a significant large effect of the operation mode on the ASQ score (p = 0.037, η_p^2 = 0.16). Post-hoc comparisons showed that the ASQ score for the autonomous operation mode was significantly lower than that for the tele-manipulation mode, with a moderate effect size (p = 0.003, d = 0.70). Compared to the shared control mode, the ASQ score for autonomous operation mode tended to be also lower; however, the difference only approached the level of significance with a moderate effect (p = 0.070, d = 0.50). A non-significant, small effect (p = 0.337, d = 0.23) was observed for the comparison between the two user-controlled modes. No significant interaction effects between subgroups of participants and operation modes were found (p = 0.491–0.826, η_p^2 = 0.01–0.03) (Table 4).

Discussion

The present study aimed to evaluate different operation modes of an assistive bathing robot. Being a representative of potential users of this robot, we recruited older persons with bathing disability and analyzed the task effectiveness and user satisfaction with three operation modes providing different levels of assistance during a water rinsing task for the user's upper back region. In addition, we explored whether different subgroups of participants were most satisfied with a specific operation mode. Our results indicate that the autonomous operation mode for the robotic soft-arm of the bathing robot is highly effective and reliable in providing water rinsing for a predefined body area. Significantly lower task effectiveness was observed in the operation modes in which the robot autonomy was lower and the robotic soft-arm motion was predominantly controlled by the participants. Task effectiveness gradually decreased along with lower assistance provided by the bathing robot. Similar findings were observed for the user satisfaction, with the highest level of satisfaction observed for the autonomous operation mode and also a tendency to a gradually decreasing satisfaction with decreasing robot assistance. Preferences for a specific operation

Table 2. Differences in the task effectiveness (coverage, step effectiveness) between the different operation modes.

		Operation mode			*Friedman ANOVA*	Post-hoc comparisons between operation modes	
	n	Autonomous operation (1)	Shared control (2)	Tele-manipulation (3)	p-value	p-value[a]	Effect size[b]
Coverage [%]	21	100.0 ± 0.0 100.0 [100.0–100.0]	79.4 ± 18.2 83.3 [33.3–100.0]	64.4 ± 19.4 66.6 [33.3–100.0]	< 0.001	0.001 (1 vs. 2) < 0.001 (1 vs. 3) 0.009 (2 vs. 3)	0.74 (1 vs. 2) 0.84 (1 vs. 3) 0.57 (2 vs. 3)
Step effectiveness [%]	21	100.0 ± 0.0 100.0 [100.0–100.0]	51.6 ± 10.3 50.3 [28.3–75.0]	43.9 ± 8.6 42.9 [27.3–62.3]	< 0.001	< 0.001 (1 vs. 2) < 0.001 (1 vs. 3) 0.016 (2 vs. 3)	0.88 (1 vs. 2) 0.88 (1 vs. 3) 0.53 (2 vs. 3)

Data presented as mean ± SD and median [range]. [a]P-values for Wilcoxon signed-rank tests. Effect size given as $r = Z/\sqrt{N}$

Table 3. Differences in the user satisfaction between the different operation modes.

		Operation mode			RM-ANOVA		Post-hoc comparisons between operation modes	
	n	Autonomous operation (1)	Shared control (2)	Tele-manipulation (3)	p-value[a]	Effect size[b]	p-value[c]	Effect size[d]
ASQ[e]	22	2.0 ± 1.0	2.5 ± 1.5	3.0 ± 1.4	0.037	0.16	0.071 (1 vs. 2) 0.003 (1 vs. 3) 0.337 (2 vs. 3)	0.50 (1 vs. 2) 0.70 (1 vs. 3) 0.23 (2 vs. 3)

Data presented as mean ± SD. [a]P-value for within-subject effect (operation mode). [b]Effect size given as η_p^2. [c]P-values for paired-samples t-tests. [d]Effect sizes given as Cohen's d. [e]ASQ, After-Scenario Questionnaire (lower scores indicate higher user satisfaction).

Table 4. Interaction effects between subgroups of participants and different operation modes on the user satisfaction.

		Operation mode			Group × mode effect	
	n	Autonomous operation	Shared control	Tele-manipulation	p-value	Effect size[a]
Age						
< 80 years	12	2.0 ± 1.1	2.4 ± 1.4	3.1 ± 1.5	0.621	0.02
≥ 80 years	10	2.0 ± 0.9	2.7 ± 1.6	2.8 ± 1.2		
Cognitive Status						
NCI	10	2.3 ± 1.3	2.5 ± 1.0	3.2 ± 1.0	0.709	001
CI	12	1.8 ± 0.7	2.5 ± 1.8	2.8 ± 1.6		
Functional Status						
High	11	1.9 ± 0.9	2.3 ± 1.0	2.8 ± 1.5	0.826	0.01
Low	11	2.0 ± 1.1	2.8 ± 1.8	3.1 ± 1.3		
Physical performance						
High	8	2.1 ± 0.9	2.1 ± 0.9	2.9 ± 1.2	0.491	0.03
Low	14	1.9 ± 0.7	2.8 ± 1.7	3.0 ± 1.7		
Fall history						
Non-fallers	10	2.0 ± 1.1	2.5 ± 1.5	2.7 ± 1.3	0.747	0.01
Fallers	12	2.0 ± 1.0	2.6 ± 1.5	3.2 ± 1.4		
Fear of falling						
Low	7	2.2 ± 1.0	2.5 ± 1.2	2.9 ± 0.9	0.734	0.01
High	15	1.9 ± 1.0	2.5 ± 1.6	3.0 ± 1.5		
Technology acceptance						
High	11	2.2 ± 1.2	3.0 ± 1.3	3.2 ± 1.0	0.647	0.02
Low	11	1.8 ± 0.7	2.1 ± 1.5	2.7 ± 1.6		

Data presented as mean ± SD. Effect sizes given as η_p^2. NCI, not cognitively impaired; CI, cognitively impaired.

mode were not observed among different subgroups of participants.

Task effectiveness with different operation modes

Our results confirmed the primary hypothesis that task effectiveness with the bathing robot would be highest in the autonomous operation mode and gradually decrease with lower levels of robot assistance. This finding supports previous studies that compared different operation modes of other assistive robots in young or older adults and also found the highest task effectiveness in the most autonomous operation modes (Erdogan & Argall, 2017; Kim et al., 2012; Koceska et al., 2019; Werner et al., 2018; Yu et al., 2003). Although the maximum possible time for completing the water rinsing task was allowed to be twice as long as in the autonomous operation mode, the body area covered in the user-controlled modes was significantly lower with only a few participants able to provide water rinsing for the whole target body area. The lower task effectiveness in the user-controlled modes was also revealed by the significant lower step effectiveness. This suggests that participants issued several inefficient commands not increasing the body are a covered by the water and that some target points on the upper back region were passed more than once or the water stream even exceeded this region (tele-manipulation mode). As expected, among the user-controlled operation modes, task effectiveness was significantly higher in the shared control mode than in the tele-manipulation mode. This finding indicates that the audio signals of the I-SUPPORT robot given for command registration and execution as well as the restriction of the robotic soft-arm motion to the predefined upper back region effectively assisted the participants in completing the water rinsing task. However, as the task effectiveness in the shared control mode was still substantially lower than in the autonomous operation mode, it seems that the robot assistance in this mode was not optimal and the required interaction was too difficult to handle for the participants. This might be explained by the fact that participants did not directly see the robotic soft-arm behind their back during the test procedure but only could imagine its spatial position and movement based on the water stream felt on the skin of their upper back. As spatial and tactile sensory abilities decline with age (Skedung et al., 2018; Techentin et al., 2014), the position determination of the water stream on the upper back might have been particularly difficult in our sample of older adults and hampered their ability to accurately distinguish between the target points on the upper back and to perceive whether all of them were reached. Providing elderly users additional direct visual or audial assistance on the real-time position of the water stream might represent a potential option for increasing their task effectiveness in rinsing water on body parts which cannot be directly seen.

User satisfaction with different operation modes

Based on previous studies suggesting that users of assistive robots seem to be more satisfied with operation modes for HRI in which they retain as much control as possible (Cooper et al., 2012; Kim et al., 2012; Yu et al., 2003), we hypothesized that the user satisfaction would be lower in the autonomous operation than in the user-controlled operation modes (shared control, tele-manipulation). Surprisingly and in contrast to this hypothesis, our results revealed that participants were, however, rather less satisfied with the user-controlled operation modes than with the autonomous operation mode, in which they had the least control and the I-SUPPORT robot fully autonomously completed the water rinsing task. A potential explanation for these findings might be the higher age of our participants, which may be associated with also a higher request for assistance when using technology than in younger populations (Kressig & Echt, 2002), or the higher differences in the task effectiveness between the operation modes, which could have been perceived much more clearly by our participants during the test procedure. As the water rinsing task was interrupted by the test administrator after a maximum of 2 min in the user-controlled operation modes, participants who could not provide water for the whole target body area might have become aware of their low task effectiveness, potentially leading to a feeling of overload that may have affected their satisfaction with these operation modes (Hauer, 2018; Tacken et al., 2005).

Given the recommendation to consider the personal characteristics when studying HRI in the heterogeneous population of older adults (Zafrani & Nimrod, 2018), we explored whether specific subgroups of participants were most satisfied with one of the operation modes. Our results revealed that there were no significant interactions of personal characteristics with the operation modes, indicating the higher user satisfaction with the autonomous operation mode were unspecific for age, cognitive status, functional status, physical performance, fall history, fear of falling, and technology acceptance. Thus, the autonomous operation mode seems to be a promising and highly satisfactory HRI option for a broad range of potential older users of the bathing robot.

Limitations

Our study has some limitations. First, the test order of the operation modes with different levels of robot assistance was not randomized, but the operation modes were tested in a fixed order with successively decreasing robot assistance (autonomous operation → shared control → tele-manipulation mode), so order effects due to learning or fatigue cannot be excluded. However, in the autonomous operation mode, the soft-arm was controlled fully automatically without user input and potential learning effects during the user-controlled operation modes might have rather favored the task effectiveness in the tele-manipulation mode, in which it was the lowest. It might, therefore, be assumed that a randomization would have even led to more obvious differences in the task effectiveness between the operation modes. Minor fatigue during the test procedure may have been occurred during the test procedure; however, as sufficient rest periods between testing the operation modes were provided, it was assumed that this has been successfully minimized. Second, the sample size was rather small, limiting the statistical power and generalizability of our results. Third, participants were predominantly females, limiting the ability to examine gender differences and the generalizability of results to male. Fourth, although the bathing process involves multiple subtasks (e.g., water rinsing, soaping, scrubbing, drying), the operation modes were evaluated only for one specific subtask (water rinsing). However, we assumed that the participant's effectiveness and satisfaction with the operation modes are independent of the subtask performed with them and rather depend on the level of robot autonomy of the operation modes.

Conclusions

The present study showed that the full autonomous operation of the bathing robot was the most effective and the most satisfying operation mode in our sample of older adults with a bathing disability. Giving the participants more control over the bathing robot significantly reduced not only the task effectiveness but also the user satisfaction with the bathing robot. These findings suggest that for an effective and highly satisfying HRI between a bathing robot and potential older users it seems to be necessary to implement operation modes with a high level of robot autonomy that requires a minimum of user input.

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Declaration of interest

The authors declare no conflicts of interest.

ORCID

Christian Werner http://orcid.org/0000-0003-0679-3227
Athanasios C. Dometios http://orcid.org/0000-0002-6897-830X
Costas S. Tzafestas http://orcid.org/0000-0003-1545-9191
Petros Maragos http://orcid.org/0000-0003-0534-2707
Klaus Hauer http://orcid.org/0000-0001-8041-5705

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