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Towards Physical Human-Robot Interaction using Force Support for Nursing Care Bed Activities

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Abstract— **This paper examines the framework conditions for safe work in physical human-robot interaction to reduce the workload of caregivers in the nursing domain. For this particular case, the transmission of forces play a major role. Because of that, currently existing standards to transmit forces to the human body are discussed. Further on, testing early robot prototypes where the robot comes into direct contact with humans is impossible due to safety concerns and thus has to be done on patient simulators. First, we analyzed the most important nursing activities to be supported by a robot manipulator. Then we conducted two experiments to find out whether a patient simulator behaves similar in comparison to a human while being mobilised by a caregiver during a nursing activity and whether conventional collaborative lightweight robots are up to the task of handling a patient without external help despite having a rather low payload capacity. The experimental results show that moving a patient simulator is more physically demanding compared to moving a human with similar weight and that conventional collaborative lightweight robots are able to push and move a patient simulator weighing 80 kg which is far higher than the robot's actual payload suggests.**

I. INTRODUCTION

Nursing shortage is an already existing problem in many countries. Demographic change means that more and more people of advanced age have to be cared for. In Germany in particular, the number of nursing staff is also tending to decline [1]. The rising number of people in need of care is being offset by a decreasing number of qualified nursing staff, so that according to forecasts there will be a shortage of more than 450.000 caregivers by 2050 [2]. One of the reasons for the decrease in workforce size is the early withdrawal from work due to musculoskeletal disorders [3]. Especially nursing activities at the bed have an enormous influence on the load acting on the caregivers' spines [4].

Common physical support tools are only of limited help in this regard. For instance, the time consuming usage of patient lifters is usually limited to the transfer to or into the bed and thus does not actively promote the patient's mobility. A further possibility of relief is the augmentation of the nursing staff's strength by exoskeletons worn on the body [5], [6]. However, an exoskeleton has the disadvantages that it must be put on before use and it is not able to replace the help of a second nurse, who is often called in for physically demanding activities. However, as mentioned above, calling a second person for help is often no longer possible due to lack of personnel. Therefore, we envision to develop a robotic assistance system that acts as a substitute for the otherwise missing second caregiver. For this goal, we designed a setup in previous work where a KUKA LBR iiwa 7 R800 was mounted to an actuated care bed which is surrounded by a multi depth camera arrangement [7] consisting of Microsoft Azure Kinect 3D cameras and a force measuring platform [8]. Additionally, as the system is not certified according to the Medical Device Directive (MDD of the European Community), a rescue dummy with the weight of an average person functions as a patient simulator in this context (see Fig. 1). In our opinion, three key aspects need to be researched in order to develop a support concept for the relief of bedside nursing staff in carrying out nursing activities:

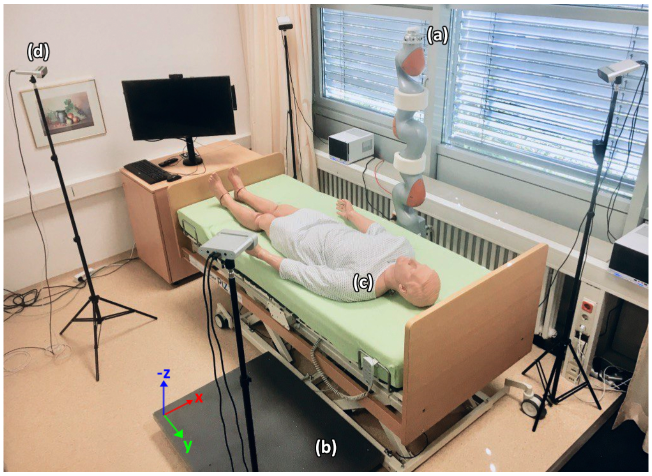

Fig. 1. Setup for the support of nursing care bed activities using a bedside mounted KUKA LBR iiwa 7 R800 (a), an AccuPower2 force measuring platform (b), a rescue dummy functioning as a patient simulator with a weight of 80 kg (c) and a multi depth camera system (d).

1) Force transmission concepts to a potentially vulnerable patient, serving a multitude of manipulations and body anatomies.
2) Detection of suitable spots to interact with the patient.
3) Operation of the robot in orchestration with the caregiver for an optimal interaction during task execution.

In this work, we mainly want to discuss boundary conditions that can lead us to the solution of the three aforementioned key aspects. An extremely relevant point is the testing of robotic support concepts in real life. However, from an

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ethical and safety point of view, it is more advantageous to initially test the robot's performance on patient simulators with human weight instead of real humans. The question whether and to what extent the handling of such a simulator differs from a real human being has to be answered, which will be examined in more detail in this work. Subsequently, we want to take a closer look at the potential of a conventional light weight robot manipulator such as the KUKA LBR iiwa 7 R800 to move a patient simulator on its own. These robots are not necessarily built to withstand the weight of people during nursing activities.

After the presentation of the related work, we will first present the results of the aforementioned nursing activity analysis. Then, the two different experiments including the comparison between a human and a patient simulator and the force transmission to move a patient are conducted and discussed.

II. RELATED WORK

The intentional contact between robot and human with additionally controlled force transmission is a rather unusual topic, which is why the number of publications for this particular subject is quite sparse, even in the field of physical Human-Robot Interaction (pHRI). In the health care domain, Erickson et al. presented a work on washing patients using a PR2 robot with the help of capacitive sensing instead of vision or force feedback [9]. The robot was able to follow and clean a human arm by following its contour while maintaining a force under a certain threshold. The capacitive sensing neural network model was trained to estimate the relative position of the closest point on a person's limb surface. For motion control, a high level Cartesian controller was used to provide joint values to the low-level proportional-integral-derivative (PID) controllers of the robot actuators. Only a few researchers have worked towards the goal of washing a patient and in most cases the they did not tackle the washing problem directly but rather developed exoskeletons [10] or bath water control systems. King et al. again developed a robot that wipes off debris of a human's upper arm, forearm, thigh or shank lying in a bed using a compliant force-controlled wiping motion without tracking but with the help of an operator [11].

Another group of works deals with the aspect of developing robots for the purpose of massaging. Here, the contact between robot and human with simultaneous application of a predefined force is intended, whereby the contact forces with the soft tissue of the human are particularly difficult to assess. Except for the bones in the human body, everything else is defined as soft tissue and can be distinguished by their different characteristics. The Young's Modulus of typical soft tissue is relatively low with a value of around $1\,MPa$ [12] and its model can be described as a multilayered, anisotropic, viscoelastic, inertial, plastic and non-stationary environment [13]. In contrary, the Young's Modulus of skin can range from $5kPa$ to $140MPa$ [12]. This shows, that it is difficult to grasp the properties in advance to a contact and that they also most likely vary from person to person based on the body composition, muscle contraction and many other factors, once again showing the complexity of soft tissue contact scenarios. Nevertheless, Golovin et al. incorporated a control method including position and force to perform the task of massaging [13]. In most pHRI use cases, a compliant robotic behaviour is desirable, which is why impedance control is often the first choice in this area [14], [15], [16].

In the context of medicine and surgery, the application of force directly on humans by robotic assistance systems is not a novelty, but the forces applied are relatively small compared to the forces occurring during the execution of nursing tasks [17], [18]. Another fitting area of work in robotics is the manipulation of objects in the environment by pushing which is usually the method of choice when the target object is too big or too heavy to grasp. Just like in the aforementioned literature, manipulation by pushing is not trivial due to the many geometrical and physical properties associated with the robot's surroundings. In general, for planning and control either a forward model or an inverse model is used to predict the next state based on an action of the current state or to compute the action that changes the current state to a desirable target state [19]. There are many different approaches to this topic, ranging from deep (reinforcement) learning [20], [21], [22], data-driven [23], [24], analytical [25], [26] and physics engine [27] based methods. Although the pushing methods presented so far cover a broad field, to our knowledge they have not yet been applied in the context of nursing, which adds a whole new layer of complexity due to safety reasons.

III. APPROACH

A. Nursing Activity Investigation and Physical Load Limits

In the beginning, a small focus group meeting was held with four people attending who had a nursing background. The reason for the meeting was, on the one hand, to identify the everyday nursing activities at the bed, which require physical effort, and, on the other hand, to explore cooperative activities, since in some cases the activity cannot be easily managed alone. The activities were also carried out in an exemplary fashion and recorded using the Azure Kinect 3D depth cameras for later analysis. The activities determined were then compared with the literature to obtain a complete representation. Then, the activities were compared with the ones used in a study by Jaeger et al. to determine the loads on the lumbar spine with the help of a biomechanical model [4]. In Table I these values are compared with the maximum recommended lumbar load for healthy and back-friendly working [28]. It is noticeable that the execution of most nursing care bed activities exceed the load limits and therefore has a negative impact on the musculoskeletal system.

Another aspect, which is of great relevance in this context, is the consideration of the maximum forces that can be applied to the human body. Due to the fact that the intended transmission of force using robots is rarely carried out, no values have yet been determined for this application. However, it is possible to fall back on safety values for

TABLE I

MEAN VALUES AND RANGES OF COMPRESSIVE FORCE ON THE LUMBOSACRAL DISC FOR THREE DIFFERENT EXECUTION MODES OF NINE NURSING ACTIVITIES BASED ON THE RESULTS OF JÄGER ET AL. [4]. THE APPROPRIATE FORCE LIMIT STARTS AT 4.1 KN FOR 20 YEAR OLD WOMEN AND DECREASES DOWN TO 1.8 KN FOR 60+ YEAR OLD WOMEN. FOR MEN THE LIMITS ARE 5.4 KN TO 2.2 KN RESPECTIVELY [28].

Nursing activity	**Conventional**	**Optimized**	**Optimized with small aids**
a. Raising from a lying to a sitting position	3.4 (1.8 - 5.4)	2.3 (1.9 - 2.9)	n.a
b. Elevating to a sitting position at the bed's edge	5.0 (3.3 - 6.2)	2.7 (2.0 - 3.6)	n.a.
c. Moving to the bed headboard with nurse at bed's side	6.7 (5.6 - 8.0)	5.4 (3.7 - 6.5)	2.8 (2.3 - 3.2)
d. Moving to the bed headboard with nurse at bed's head	5.7 (2.8 - 8.9)	2.5 (2.0 - 3.0)	2.4 (2.2 - 2.8)
e. Moving sidewards	4.9 (3.3 - 5.8)	2.6 (2.0 - 3.4)	1.9 (1.6 - 2.2)
f. Raising the bedhead	4.3 (3.8 - 5.4)	4.1 (3.5 - 5.2)	n.a.
g. Assisting with a bed-pan	4.2 (2.6 - 6.5)	2.6 (1.6 - 3.3)	n.a.
h. Moving from the bed into a chair	5.1 (3.8 - 6.5)	3.7 (2.3 - 4.4)	3.1 (1.6 - 5.3)
i. Raising from sitting to an upright position	4.9 (3.8 - 6.4)	2.5 (1.9 - 3.1)	n.a.

collisions with robots for the time being. Table II shows the maximum permissible forces in Newtons per body region, which are derived from DIN ISO/TS 15066 [29].

To validate the physical relief, in our case a force measuring platform is placed in front of the bed in the nurse's work area. This does not allow a direct comparison with the results of the biomechanical model of Jäger et al. [4], but it is possible to have a look at the measured ground reaction forces of the nurse to draw conclusions from these data. Furthermore, a good picture of the overall force distribution can be generated with the torque data from the individual robot joints, so that physical relief becomes quantifiable.

TABLE II

BODY CONTACT FORCE LIMITS BASED ON [29].

Body region	**Maximum permissible contact force [N]**
Head	130
Face	65
Neck	150
Back	210
Shoulders	210
Chest	140
Abdomen	110
Pelvis	180
Upper arms	150
Forearms	160
Hands	140
Thighs	220
Calves	210

B. System Infrastructure

The physical components of the used robotic support system consist of a robot (KUKA LBR iiwa 7 R800), a robot controller (KUKA Sunrise Cabinet), a computer for the communication using the Robot Operating System (ROS) [30] and a vision system (Microsoft Azure Kinect 3D Camera) (see Fig. 2). For additional measurements, a force measuring platform is used. We also make use of the Fast Robot Interface (FRI) for a better and faster signal control loop, which is proving to be very beneficial when dealing with force control systems. One disadvantage, however, is the limited communication with the KUKA Sunrise Cabinet. Using the FRI it is no longer possible to switch between different control modes at runtime, e.g. switching from position to torque control. Once the connection has been established, either a position, wrench or torque command mode can be used. For our task, we choose the position command mode with a impedance control where a joint stiffness of 1000 is set. In this command mode, the response rate is less or equal than 10 ms. The impedance control scheme is used because it enhances safety where humans have to share a workspace with robots [31].

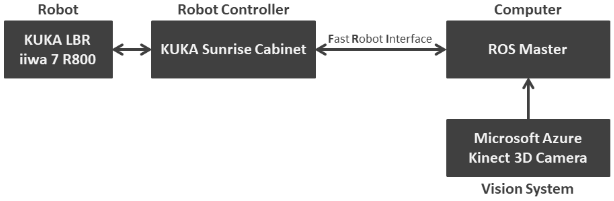

Fig. 2. Overview of the used infrastructure to control the robot.

IV. EXPERIMENTS AND RESULTS

A. Handling Comparison Between a Human and a Patient Simulator

The creation of a realistic test scenario is an important factor for many areas of robotics. While many scientific papers deal with the generalization of robot behavior and try to represent the real world in simulations, real data remain irreplaceable for testing purposes for the time being. Especially manipulation tasks are very difficult to reproduce in simulations due to the complexity caused by the direct contact with all associated physical parameters [20]. This makes testing and data collection in the real world all the more important. In the case of pHRI, however, this turns out to be problematic, since in development the collection of data directly on humans should be circumvented for reasons of safety and ethics. This problem has been recently recognized for assistance robotics and there exist approaches to collect data directly on human models from robots in simulation [32]. In addition to simulation, data collection in the nursing context in the real world would also be conceivable with patient simulators, for example.

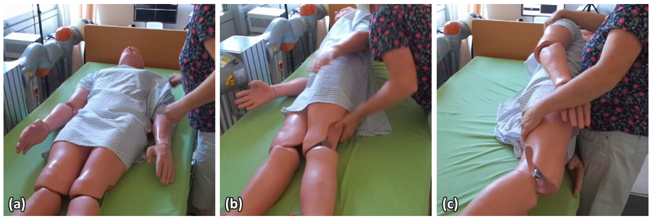

Fig. 3. Process of the experiment to determine the differences between handling either a patient simulator or a human. A nurse is standing on a force measuring platform (a) while turning the patient to each side (b-c) during the process of moving towards the bed's headboard.

Since no other work has yet made a comparison with regard to the forces acting between patient simulators and humans, we will make this comparison with the infrastructure described before. For the purpose of this comparison, the strenuous activity of moving the patient to the bed's headboard when standing at the bed's side was performed by a caregiver while standing on a force measuring platform (see activity c in Table I and Fig 3). The activity was performed five times with a 80.5 kg person and a 80 kg patient simulator. The process is divided into two steps: The lying person or the lying patient simulator is first turned to the side in the direction of the nurse and is moved slightly towards the headboard when the person is put back on his back. Then the same movement is repeated, but this time away from the nurse. The entire process is also recorded by a depth camera, so that the times of the two turning processes can be tracked exactly for a precise analysis. The resulting forces of one pass can be seen in Fig. 4. In all five passes, the two body turning activities were analysed both individually and together for every axis, which can be seen in Table III. In particular, the arithmetic mean value, standard deviation, minimum and maximum values were calculated for further inspection. If one compares the two turn activities with each other, it becomes clear that the second turning event of the patient requires less effort in the case of the human and more effort in the case of the patient simulator. This becomes particularly obvious by looking at the forces in the direction of the z-axis which is 5.27 times higher. Also, the overall standard deviation is slightly larger during the first turn activity. Furthermore, the minimum values when moving a human are approximately the same during both turns with a small difference of 8.8, the values while moving the patient simulator are much further apart where the average value for the first turn is -130 while the second turn has a value of only -24.1. In both scenarios, the first turn activity has a higher value for the maximum values, but the difference is greater for the human with a value of 65 at the first turn while the difference for the patient simulator is only 18.37. As expected, the maximum values also show the highest peak load of 310.8 on average for the human and 388.7 for the patient simulator in the direction of the x-axis of the force plate, which is most likely due to the leverage when pulling the patient during the first turn. This high value can also be found in the overall force, especially in the x-axis component. This is also where the two most important statements regarding the validity of the data can be found: first, the x-axis component of the force data has very high values during the execution of the task and. Second, turning towards the nurse - i.e. the first part of the activity - is more strenuous in both scenarios. Third, moving the patient simulator is more strenuous than moving the human being of an almost identical weight. On average, turning towards the nurse is 1.28 times more difficult using the patient simulator according to the measurement and even 2.74 times more difficult when during the turn away activity. Interesting at this point, however, is the difference in the load peaks, which are given by the maximum values. During the first turn activity we measured a 1.2 times higher maximum force when handling the patient simulator, during the second turn activity it is even 1.57 times higher. It can be concluded from the results that in the process of placing the patient on his side, the patient simulator with an almost identical weight cannot reproduce the kinematics, material characteristics or loads of a real human being. This experiment suggests that for a test environment similar to that of a real human being, the patient simulators either need to be equipped with better mobility or they need a lower weight in order to map the potential load forces for a person with more weight. It must be said, however, that the experiment is limited to the performance of one specific nursing activity and the results may vary significantly for other activities.

TABLE III

RESULTS OF THE COMPARISON BETWEEN THE HANDLING OF A PATIENT SIMULATOR AND A HUMAN DURING THE NURSING ACTIVITY OF MOVING A PATIENT TOWARDS THE BED'S HEADBOARD IN TWO INDIVIDUAL STEPS.

	Human: 1st turn	**2nd turn**	**Patient Sim.: 1st turn**	**2nd turn**
$\varnothing F[N]$	51.7	39.2	66.6	107.6
$\varnothing F_x[N]$	112.9	52	156.4	135.3
$\varnothing F_y[N]$	21.5	30.7	19.4	60.2
$\varnothing F_z[N]$	20.6	35	24.1	127.2
$\varnothing SD[N]$	62.2	55.7	87.6	57
$\varnothing SD_x[N]$	85.8	49.2	124	43.6
$\varnothing SD_y[N]$	66	80.7	68.8	61.2
$\varnothing SD_z[N]$	34.8	37.2	70	66.1
$\varnothing Min[N]$	-93.8	-85.0	-130	-24.1
$\varnothing Min_x[N]$	-21.8	-24	-59.4	35.1
$\varnothing Min_y[N]$	-174.4	170.2	-162.8	-83.6
$\varnothing Min_z[N]$	-85.3	-60.9	-167.8	-24.7
$\varnothing Max[N]$	221.6	156.6	265	246.63
$\varnothing Max_x[N]$	310.8	155.9	388.7	214
$\varnothing Max_y[N]$	188.4	178.9	220.7	218.8
$\varnothing Max_z[N]$	165.7	134.9	185.4	307.2

B. Maximum Robot Load for Physical Human-Robot Interaction

Another important aspect, which is necessary for the investigation of pHRI in the field of physical assistance in care, is the payload or the potential of the robots to move larger masses. It is well known that robots are capable of moving large masses. However, the potential maximum payload depends on the design of the robots, the configuration of

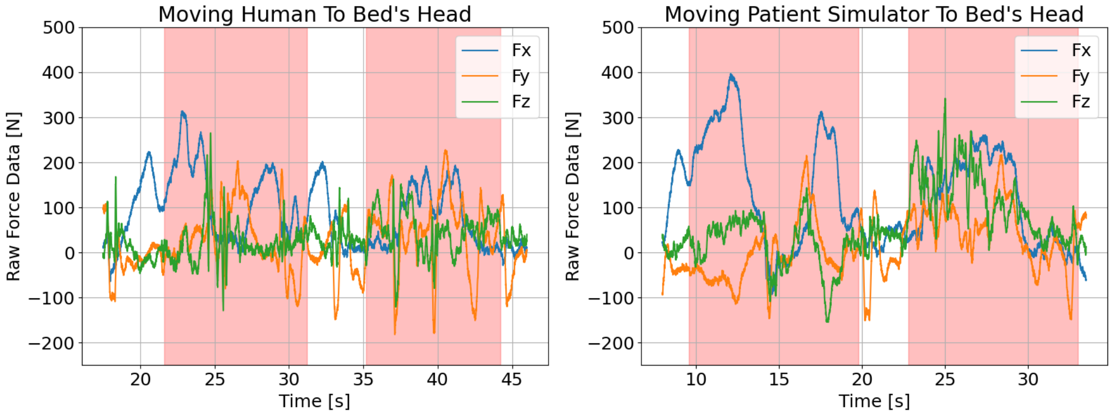

Fig. 4. Raw force data (x, y and z axis) recorded while a nurse moves a human or a patient simulator towards the bed's headboard. The activity mainly consists of two turn movements (areas marked in red) which have been annotated using the data of a depth camera recording.

Fig. 5. The setup of the robotic load experiment where the robot tries to push the 80 kg weighing patient simulator without any external help. The pushing starts at about 2.4 seconds and ends after 12.2 seconds. The torque for every joint during the execution is measured.

the robot in respect to the patient and the maximum torques at the relevant joints. In nursing, however, it is also necessary to have enough space for the collaborating nurse. The keyword ”collaborating” is particularly important here, since most collaboration robots are built smaller and have lower payloads than common industrial robots. In our example setup, an iiwa manipulator with a maximum payload of 7 kg is used. However, for health care support, the robot has to cope with the patients' weight to provide physical relief. For this case we have carried out a joint load test experiment, where the robot manipulator should independently move the patient simulator by pushing it within the bed. To be more precise, the robot's start position $\boldsymbol{q}_{start}(t)$ and goal position $\boldsymbol{q}_{goal}(t)$ in joint space have already been defined in advance so that we only have to deal with the Cartesian movement between these positions. In addition, we are only considering the translational component of the movement, breaking it down to a one dimensional motion along the Y-axis relative to the robot's base frame. For the experiment, the end effector presses on the upper arm of the patient simulator and thus moves it sideways by an amount of about 10 cm without additional help (see Fig. 5). The resulting external torques at the individual joints were observed over time (see Fig. 6). The experiment was repeated 8 times and in all experiments it was possible to move the 80 kg patient simulator by about 10 cm without external help. The experiment carried out reveals two important points: first, the robot's payload is not decisive for the maximum applicable force to move masses and second, it is necessary to optimize both the configuration to support without disturbing the caregiver and the joint loads of the robot for maximum exploitation of the push potential to maintain $\boldsymbol{\tau}_{min}(t) \leq \boldsymbol{\tau} \leq \boldsymbol{\tau}_{max}(t)$ due to the robot's maximum allowed joint torques in Newton meters, being 176, 176, 110, 110, 110, 40 and 40 for the used robot manipulator beginning from the robot's first joint (base) to the last joint (end effector). This is very important because in the context of nursing care, any robotic support movement will have to deal with the problem of applying a predefined force on one or more body parts of the patient to cooperate with the nurse during the task execution to finally provide physical relief. The complexity of the trajectories while applying the forces can arbitrarily increase or decrease and is not dependent on the actual force transmission itself except in relation to the force limit values, which must be adjusted regarding the selected body part as shown in Table II. As already stated before, our system uses the FRI in order to achieve a control loop frequency of up to 1 kHz. However, this also limits the obtainable robot information so that only the individual external joint torques can be acquired. For nursing care, it would be best to make assumptions about the Cartesian end effector forces without using any additional sensors. For this particular case, it is possible to predict the forces by using the relationship between applied end effector wrenches and applied forces and torques to the joints as in [31]

$$\boldsymbol{\tau} = \boldsymbol{J}(\boldsymbol{q})^{\top} \boldsymbol{f} \tag{1}$$

where $\boldsymbol{\tau}$ is the forces and torques vector for a robotic manipulator of n degrees of freedom (DOF), $\boldsymbol{J}^{\top}$ is the transposed Jacobian matrix and $\boldsymbol{f}$ is the end effector force

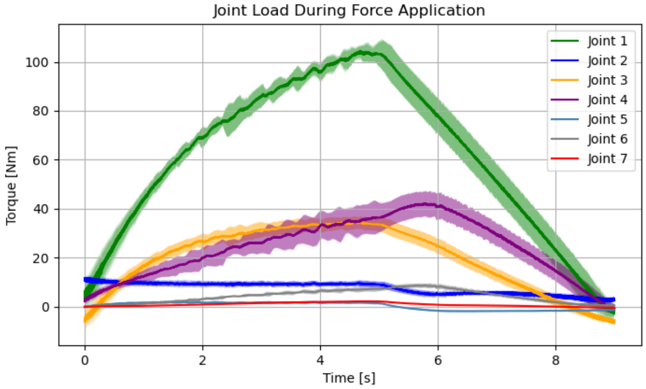

Fig. 6. Visualization of the joint torques during the robotic load experiment where the robot applies a force to move the 80 kg weighing patient simulator. Mean torques of every joint and lower and upper error are visualized.

vector. To get the actual Cartesian end effector forces it is possible to make use of the Moore-Penrose inverse to finally get

$$\boldsymbol{f} = (\boldsymbol{J}(\boldsymbol{q})^{\top})^{-1}\boldsymbol{\tau}. \tag{2}$$

In real care scenarios using a robot, the support movement should make use of the force measurements to constantly update the position along a predefined trajectory to maintain the applied force below the desired threshold depending on the individual body part, the values for each can be found in Tab. II [29].

V. CONCLUSION

In this paper we were able to collect important aspects for the approach to the topic of pHRI in the care domain. There is a general need for physical relief in care. For this relief through robotic assistance, however, a force application directly or indirectly on humans is necessary. Safety standards with values for force limits depending on the body part do already exist but these were not created with the intention of providing relief in care and are currently only means to an end. It requires a systematic creation of care-related force limits. When testing care-relevant robotic support movements, initial experiments using humans is not desirable and one should switch to patient simulators for this particular task. In the present paper, however, it could be shown that there is a mismatch between patient simulators and humans, which must either be taken into account or developments in this field must take place so that simulators become more similar to humans with a suitable weight, material and mobility. Finally, we were able to show that even collaborative lightweight robots can apply enough force to independently move an 80 kg patient simulator in bed and are thus also suitable for nursing activities.

VI. FUTURE WORK

The presented work should serve as a basis for the field of pHRI for nursing care and should also show that despite existing gaps in the framework conditions, there is a potential for force relief of caregivers by collaborative robots. In future work, we will focus on directly supporting caregivers using robots and on measuring and comparing the degree of potential physical relief. For this, the three main difficulties in this complex project mentioned at the beginning have to be considered more intensively in follow-up work. On the one hand, an additional assessment of physical properties may possibly provide an advantage in the transmission of force, on the other hand, nursing activities at the bed are such highly complex activities that this problem should perhaps be handled by a controller learned through reinforcement learning rather than using a handcrafted controller. Overall, there are still many areas where the present system can be further improved and used for research. We envision a system which ensures significant physical relief through human-robot interaction and cooperation while maintaining safety standards with regard to maximum force limits dependent on the patient's condition.

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