Initial Development of Direct Interaction for a Transfer Robotic Arm System for Caregivers

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***Abstract*—The most common injuries in healthcare are related to transfers. The Strong Arm system assists caregivers in providing fully dependent transfers from an electric power wheelchair to a bed, shower bench, toilet or other surface. However, this system currently controlled by buttons could be more successful with a more intuitive method during use. This paper presents the initial development of direct interaction for a robotic transfer system called Strong Arm. Direct interaction was used to make a transfer system more intuitive to operate using a three-axis load cell. To move Strong Arm, the user must apply intentional force on any of the given axes by surpassing the axis threshold. Unintentional movement could lead to injury. The results indicate that the thresholds for each axis were at least 3.5N in X, 16.9N in Y and 5.3N in Z in order to prevent unintentional forces from a human hand that would cause the robot to move.**

Keywords—Direct Interaction, Strong Arm, Assistive Systems, Transfers

I. INTRODUCTION

Healthcare in the U.S. is becoming increasingly dependent on caregivers. Over 16.1 million formal caregivers are expected in the U.S. by 2020; this will be a 47% increase from 2010 [1]. Formal caregivers included are nursing aides, attendants, personal care aides, and home health aides. Informal caregivers (i.e. family and relatives) provided the equivalent of $450 billion worth of care in 2009 to their adult parents and other loved ones [2]. The estimated number of informal caregivers in the US is 29 million and the average age for a caregiver is 48 years old [3]. Along with other tasks, caregivers must help with repeated transfers to and from wheelchairs. This process puts a heavy strain on caregivers. Unfortunately, the most common injuries reported in healthcare are caused by overexertion during patient handling (e.g. patient transfers) [4].

Caregivers could reduce the risk of injury when transferring patients by minimizing the number of manual transfers and using transfer systems such as ceiling lifts instead [5]. Current transfer systems, such as the Hoyer lift, allow caregivers to move individuals in and out of the wheelchair to another comparable surface[6], but Hoyer lifts cannot be transported and do not perform well in confined spaces. A new transfer system referred to as the Strong Arm, from the Human Engineering Research Laboratories, is a robotic arm appended to a wheelchair to work cooperatively with caregivers for ease of transport and transfers [7].

A. Interaction

Currently, users are required to interact with most assistive systems through a joystick, voice recognition system, head switches, or a keypad [8]. Early versions of the Strong Arm could only be used with a keypad to control the movements of the robotic arm. Using the keypad, buttons were pressed to determine which joint of the robotic arm to move. This process involved mentally mapping the keypad to the robot's movements and was prone to many errors until the user had extensive experience with using the device. Existing input methods to control assistive robots tend to be slow and challenging for some people. People are more likely to abandon devices that they have a negative attitude towards or find difficult to use [9]. Thus, a more intuitive approach to control Strong-Arm was pursued. One approach to human-robot interaction is through cooperative manipulation schemes which examine the user's intent along a preplanned path [10-11]; this would be an ideal approach when lifting heavy loads. However, movement only along a path severely restricts the user's freedom to manipulate the robot. Kmetz, Markham, and Brewer [12] developed a more flexible and direct interaction approach using a user's intent to interact with robots. A touch-sensitive skin enabled users to manipulate an assistive robot in multiple directions, giving more freedom than cooperative manipulation schemes. Direct interaction is a way for humans to intuitively manipulate robots via touch and force. In manipulation activities, applied forces are vital for measuring human intent [13]. This supports the consideration of the use of a force sensor to devise a method to implement an intuitive method of interaction. Direct interaction may be more helpful and intuitive than using keypads to control some assistive systems. The purpose of this paper is to describe the initial development of a direct interaction feature implemented in Strong Arm.

II. STRONG ARM

Strong Arm is a robotic arm used to assist caregivers in providing fully dependent transfers from an electric power wheelchair to a bed, shower bench, toilet, or other level surface. As seen in Figure 1, Strong Arm removes the load from the caregiver by bearing the wheelchair user's weight.

The caregiver must first put the sling around the person and attach the sling's straps to Strong Arm. After that, the caregiver can then lift the wheelchair user from the seat to their destination via controls [14]. Table 1 indicates the joints of the system and their axes. This robot has 5 degrees of freedom (DOF). The first DOF is the carriage that allows Strong Arm to move around the back and sides of the seat. Figure 1 shows the second DOF, the shoulder's rotational joint, which allows the arm to rotate 180 degrees away from the wheelchair seat. The third DOF is a prismatic joint that allows the shoulder to elevate up to 0.23meters (9 inches). Figure 1 also shows the fourth DOF, a rotating elbow connected to the shoulder that can rotate from approximately 44 degrees, the farthest it can be pointed down to approximately 90 degrees when parallel to the ground. The fifth DOF is a prismatic joint that allows the elbow joint to extend up to 0.23meters (9 inches). The ranges of joints 2-5 are due to mechanical limitations. Encoders are attached to measure the position of the robot and are connected to a single board computer with a customized relay board. The relay board converts logic signals from the computer to control the relays connected to the linear actuators that operate the Strong Arm.

A. Hardware

Strong Arm is comprised of four linear actuators which can support loads from 1500N-3500N range. There are off-the-shelf robotic arms meshed with assistive systems that have more range of motion and greater compliance than Strong Arm, but they have limited payloads. The Whole Arm Manipulator by Barrett Technologies has a maximum payload of 39.2N with 4DOF. JACO a robotic manipulator arm by Kinova maximum payload is 14.7N with 6DOF [7, 15]. The payload limit is the only disadvantage that prevents us from using such devices. Strong Arm is much more rigid, but can hold a much greater weight capacity with a maximum payload of 1,112N (250lbs).

The handle used for direct interaction is an ergonomic plastic handle with a 4" grip with a diameter of 1.5". The handle is located at the end-effector of the robotic arm. A button on the end of the handle toggles between modes I and II (see Figure 2).The handle is mounted on a multi-axis load cells used to read the forces applied to the handle [16]. There are two multi-axis load cells (ATI Industrial Automation); one located at the base of the robotic arm and the other at the end effector. The ATI Omega load cell at the base can hold up to 7200N (1600lbf) with a resolution of 1 1/2N (5/16lbf) in both X and Y axes. The maximum load in the Z axis is 18000N (4000lbf) with a resolution of 3N (5/8lbf). The ATI Delta load cell at the end effector can achieve a reading of 660N (150lbf) with a 1/8 N (1/32 lbf) resolution in both the X and Y axes. The maximum force on the Z axis is 1980N (450lbf) with a resolution of 1/4N (1/16 lbf). The load cell is connected to the Interface Power Supply box, which conditions the load cell signals [14].

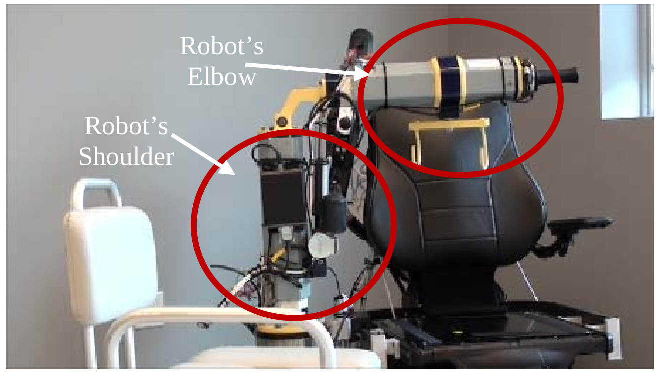

Fig. 1. Strong Arm in the upright position

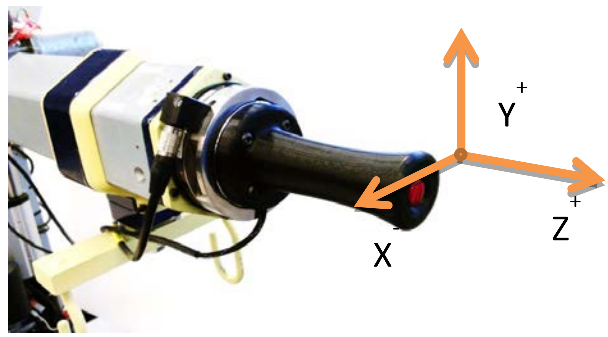

Fig. 2. The handle for direct interaction showing the axes of actuation

B. Software

Data were collected using Wind River VxWorks real-time operating system platform on a single board computer Cobra EBX-12 from VersaLogic Corporation. The data collected included forces and torques of both the load as well as the positions of all of the joints in the robotic arm relative to the position of the carriage. The values of the calibrated data were used in the interaction method described below.

III. Intuitive Interaction Design

The overall goal is to make Strong Arm intuitive for the caregiver to operate and to ensure the robot does not move unintentionally. To move the Strong Arm, the caregiver must place a hand on the handle and apply intentional force. The movement of Strong Arm will comply with the force that the caregiver applies to the handle in any of the orthogonal directions (Figure 2). A small delay is added to the response time of the algorithm to prevent the arm from moving via unintentional touch. As mentioned above, the button at the end of the handle toggles the system between Mode I and Mode II to allow all five joints to be controlled using the three axes of the load cell. To make this device intuitive for the user, the robot moves in the direction of the user's force. For both modes, when force is exerted along the x-axis the robotic arm will rotate about the shoulder's rotational joint in the direction away from the user's force. In Figure 1, if the user is standing in front of the chair and pulls the handle, the robotic arm will rotate left about the shoulder's rotational joint, moving the arm away from the wheelchair. If the user pulls the handle in the Y-direction towards the ceiling, the robotic arm will respond by actuating the rotational joint of the elbow in Mode I. Conversely, pushing the handle down towards the ground moves the elbow down in Mode I. When the button is pressed, Mode II is selected and the same intended forces along the Y-axis will raise the shoulder's prismatic joint. The scenario is similar for the Z axis, which actuates the prismatic elbow joint in Mode I and moves along the carriage in Mode II.

TABLE I.

Axis	**Joint Actuation Modes**	
	Mode I	***Mode II***
X	Shoulder Rotation	
Y	Elbow Elevation	Shoulder Elevation
Z	Elbow Extension	Move along carriage

A. System and Controller Logic

A simple algorithm has been implemented to enable Strong Arm to move one joint at a time. The input values to the algorithm are all the forces of the load cell along with the selected mode fed into the controller. The controller then decides which joint should be actuated and moves the robot to a new position as shown in Figure 3. Figure 4 shows the controller logic. If any of the forces exceeds the selected threshold value, the motor will turn on to actuate the specific joint. Once the force goes below the threshold, the motors halt and Strong Arm becomes immobile. For example, if Mode I is selected and the current force in the Z-axis exceeds the threshold set to actuate the elbow's prismatic joint, the joint moves until the force is below the threshold or the limit is reached. The robot moves in the same direction as the applied force.

After performing several movements with this algorithm, there were sudden start and stop movements between two joints. This had to do with the natural hand movement moving along one axis naturally, but unintentionally applying force along a second axis. For instance when pulling to the left, both x and y axes might receive enough force to exceed their respective thresholds, resulting in what seemed to be sporadic movement of two joints at the same time. This would happen when the force was not directly aligned on any one axis. To mitigate this unwanted movement, an additional layer of code was added to the control logic to ensure single joint control. Prior to examining which force exceeded its threshold, the algorithm had to determine which of the three axes had priority. There were two algorithms to help determine priority. In one algorithm, if Fx exceeds its threshold while another force Fy already exceeded its threshold, Fx will take precedence in movement. No other joint would be able to move until Fx is no longer above its threshold. The same approach was replicated for each axis. The second algorithm set the priority based on which axis exceeds its threshold by the greatest amount. In this manner, if two thresholds were exceeded at the same time, only the axis with the greater difference between the applied force and the threshold took precedence, resulting in a single joint control algorithm. This helped to reduce the chatter between two axes. These two approaches can later be tested to see which the caregiver would be more inclined to use.

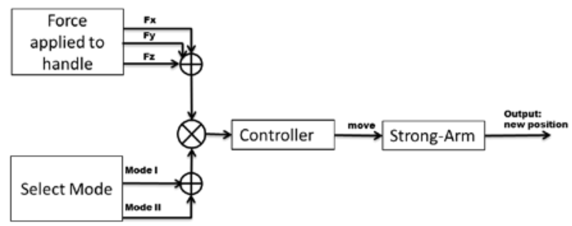

Fig. 3. System logic of the control algorithm.

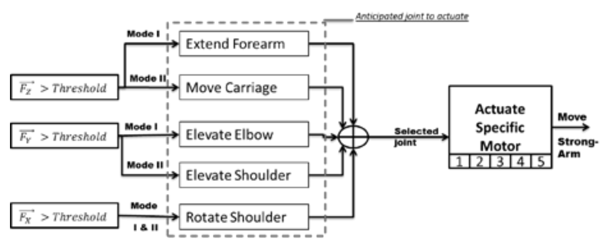

Fig. 4. Control logic of the control algorithm.

B. Thresholds

Issues may arise with unintentional movements such as the robot being hit accidentally, a person resting their hand on the handle, or a firm grip on the handle just before moving the robot with intention. For safety and to remove ambiguity, thresholds were set to ensure that the robot does not move unintentionally. Data were analyzed to see what would happen when the handle was firmly gripped, but no intention to move was made. At the start of each trial the less dominant hand was placed on the handle and gripped the handle firmly for five seconds with the handle parallel to the ground and about 90 degrees from the shoulder joint. The handle was then released for five to seven seconds and then pressed firmly again with the dominant hand. This procedure was repeated at least 5 times with a one minute break in between each set. A similar procedure was done for the handle pointing straight down at its limit (44 degrees from the shoulder). The purpose of this was to simulate a grasp at two extreme positions where gravity would play a factor in the unintentional movement after the hand is placed on the handle. This data provided information about what values to set the thresholds to reduce unintentional movement.

When placing the hand on the handle at the position parallel to the ground most of the force should be along the y-axis, because it is parallel to the gravitational force. After placing the hand on the handle while in the down position, most of the force should be applied in the z-axis because it will then be closer to being parallel to the gravitational force. Each time the hand is placed on the handle, forces are applied on each axis. This may be in response to the handle being bolted on the load cell, which causes some of the forces to be applied in all axes whenever the handle is pulled.

As shown in Table II, the results revealed that average force in the Y direction was 16.9N ± 1.8N (mean ± standard deviation). The average force in the X direction was 1.8N± 1.8N, the average force was 1.3N ± 3.6N in the Z direction. When a hand is placed on the handle with no intention to move, but the handle is not gripped firmly, the results are as follows: X axis 0N ± 1.3N, Y 15.1N ±1.8N, and Z 0N ±1.3. When the handle is pointed straight down at its limit (33 degrees from the shoulder) and the handle is firmly gripped, the mean forces were 3.5N ±1.8 on the x-axis, 14.7N ±2.2 on the y-axis, and 5.3N ±1.8 on the z-axis.

Based on the results, the thresholds for each axis is at least 3.5N in X, 16.9N in Y and 5.3N in Z in order to prevent unintentional forces from causing the robot to move. Once the force exceeds a threshold, the caregiver is able to move the particular joint in the intended direction. As soon as the force applied to the handle is less than the threshold, the robotic arm becomes immobile until threshold is exceeded once more. Final threshold values were obtained by adding 0.9N (0.2lbf) which is more than half the average standard deviation 0.8N (0.2lbf) of all axes. The following are the current thresholds to actuate each joint: Z is 6.2N (1.4lbf), Y is 17.8 (4 lbf), and X is 4.4N (1lbf).

TABLE II.

Threshold Results	**Forces In Each Axis**		
	X	***Y***	***Z***
Firm grip Average Forces at 90 degrees	1.8 N ± 1.8 (0.4 lbf ± 0.42)	16.9N ± 1.78 (3.8lbf±0.4)	1.3N ± 3.6 (0.3 lbf ±0.8)
Weak grip Average Forces at 90 degrees	0N ± 1.3 (0 lbf ± 0.3)	15.1N ± 1.8N (3.4 lbf ±0.4)	0N±1.3 (0lbf ±0.3)
Firm grip Average Forces at 33 degrees	3.5N±1.8N (0.8lbf ± 0.4)	14.7N±2.2 (3.3lbf ± 0.5)	5.3N±1.8 (1.2lbf ± 0.4)

IV. DISCUSSION

Currently, many assistive systems are operated with keypads and joysticks. It is important for the caregiver to reduce their cognitive load to reduce frustration that may ultimately result in technology abandonment. Reasons why people abandon assistive technologies may include difficulty of use, complex instructions, insufficient training, and discomfort [17]. It is important for caregivers to operate the assistive devices as efficiently and comfortably as possible. This work described a preliminary approach to provide intuitive interaction between Strong Arm and a caregiver. This new method is expected to help caregivers assist with transfers from wheelchairs to showers, beds, and chairs. Each joint actuation was assigned to mode I or II based on personal judgment. Within each mode, each joint was assigned to a particular axis of the load cell based on which axis was closest to the direction of the movement.

The current algorithm solely supports single joint control. The next phase of this project will move towards multiple joints concurrently.

Data collection is pending to validate whether caregivers prefer this direct interaction method for transfers or a mechanical lever on a commercial manual Hoyer lift. This user study will have the caregivers transfer a rescue mannequin to and from a bed, toilet, wheelchair, and shower bench, which are common for Activities of Daily Living. Feedback from qualitative data will be considered for appropriate future modifications to Strong Arm and its control.

A current limitation of Strong Arm is the lack of feedback to the caregiver in which joint is active to be used. Visual feedback such as a graphical user interface or LEDs may help to provide better indication to the user in which joint is active. Various approaches will be considered for the advancement of Strong Arm. Future work includes evaluating which mode the caregiver uses the most during a transfer. To determine how to best reduce cognitive load, future work may also include changing the mapping between the load cell and the joint movements in order to determine which axis is best coupled with each joint. The results of user studies will be used to further develop an intuitive control method for Strong Arm.

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