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SUPERNUMERARY ROBOTIC FINGERS AS A THERAPEUTIC DEVICE FOR HEMIPARETIC PATIENTS

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ABSTRACT

Patients with hemiparesis often have limited functionality in the left or right hand. The standard therapeutic approach requires the patient to attempt to make use of the weak hand even though it is not functionally capable, which can result in feelings of frustration. Furthermore, hemiparetic patients also face challenges in completing many bimanual tasks, for example walker manipulation, that are critical to patients' independence and quality of life. A prototype therapeutic device with two supernumerary robotic fingers was used to determine if robotic fingers could functionally assist a human in the performance of bimanual tasks by observing the pose of the healthy hand. Specific focus was placed on the identification of a straightforward control routine which would allow a patient to carry out simple manipulation tasks with some intermittent input from a therapist. Part of this routine involved allowing a patient to switch between active and inactive monitoring of hand position, resulting in additional manipulation capabilities. The prototype successfully enabled a test subject to complete various bimanual tasks using the robotic fingers in place of normal hand motions. From these results, it is clear that the device could allow a hemiparetic patient to complete tasks which would previously have been impossible to perform.

INTRODUCTION

Every year, more than 700,000 people in the US experience one or more strokes and 90% of the survivors live with impaired upper limb functions, often in the form of hemiplegia or hemiparesis [1]. For these people, one third of whom are younger than 65 years old, rehabilitation training during the early phase of recovery (< 6 month) has been the only therapeutic approach to regain lost motor skills. Robot assisted therapy, providing intensive, repetitive, and interactive treatment that can be objectively monitored from an early stage, was developed to more effectively and efficiently aid patients in motor recovery. The MIT-Manus [2], the Mirror Image Movement Enabler [3], the Bi-Manu-Track [4], and the NeReBot [5], just to name a few, have shown evidence of improving upper limb motor function in patients suffering from acute and subacute stroke; whether the training also results in significant improvement in performing activities of daily living (ADLs), however, still remains to be verified [6].

In a JRRD review, Masiero et al. pointed out that among the robotic interventions that had gone through at least one randomized controlled clinical trial on patients with acute and subacute stroke, large functional independence can be measured when robot intervention is used in conjunction with conventional therapy [7]. This is perhaps due to the fact that robotic intervention mostly focuses on repetitive general movements, whereas conventional therapy also teaches and trains strategies in performing different ADLs, an essential step to regaining independence and reintegrating into domestic life. Unfortunately, ADL training is often met with frustration as the patient attempts to make use of the weak or immobile hand, especially for bimanual tasks. Frequent failures in completing simple tasks may aggravate post-stroke depression, an after-effect observed in nearly 30% of the patients, and further negatively impact rehabilitation processes and outcomes [8, 9].

We developed a wearable robot for assisting occupational therapists in ADL training. Unlike our previous work on Supernumerary Robotic (SR) Fingers, which investigated natural and implicit control of wearable fingers mounted on the

remaining healthy hand for independent, one handed grasping and manipulation [10–12], the new robotic finger design focuses on rehabilitation of the impaired hand. The patient wears the SR Fingers on the paretic forearm and controls the opening and closing of the robotic fingers with the healthy hand, which is monitored by a sensor glove. As the patient goes through ADL training, he/she can try to move the impaired arm and reach for objects in manners similar to those of conventional therapy. When the arm is near the object, the patient can actuate the robotic fingers to grasp it, allowing for object retrieval or further bimanual manipulation even if the affected hand is not yet completely capable. The aim is to provide patients with a sense of purpose and accomplishment during ADL training, even during the early phase of treatment when the task can only be partially completed. We hope that this device can facilitate therapist-guided ADL training and encourage patients to continue exercising the affected limb without experiencing a continual sense of failure.

The remainder of this paper presents a) the design of a new SR Finger prototype as a grasping aid during ADL rehabilitation training, b) a simple and intuitive control scheme that allows the patient to switch between different training goals, and c) evaluation of the device as test subjects perform a variety of ADLs.

PROTOTYPE DESIGN AND DEVELOPMENT

The prototype device, consisting of two robotic fingers that aid the patient in grasping tasks, was designed to be worn on the non-functional hand. The robotic fingers share the same workspace as the impaired human fingers. Thus, the patient is able to position both of their hands in the same natural poses they would normally use to complete a task. This encourages the patient to simulate performing the task themselves, while the robotic fingers assist in the successful completion.

The robotic fingers were designed only to aid in human grasping and not to perform the task alone. For this reason, the device only includes two robotic fingers, and the grasping action is accomplished using the human palm as a ground. This allows minimal interference with the human fingers and a grasp posture that closely matches the natural one. Figure 1 shows the device orientation with respect to the human hand. The frame was 3D printed to provide an ergonomic shape for patient comfort as well as a compact mount for the actuators.
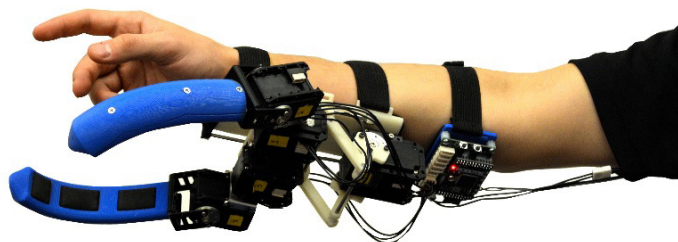

Fig. 1: Wrist mounted SR Finger prototype developed to assist with therapist guided ADL rehabilitation training.

Each of the SR Fingers has two degrees of freedom (DOF). These two DOFs are along the same axes as those at the base of the human finger, the metacarpophalangeal joint. The number of DOFs was chosen as the minimum number necessary to span the typical workspace of an object when it is within reach of the hand. The finger itself did not include any additional DOFs for the knuckle joints as these were not necessary for most grasping tasks, and the weight of the fingers needed to be minimized for comfortable wear. An additional DOF was incorporated in the base of the SR Fingers to enable translation along the bottom of the forearm and allow the SR Fingers to adapt their workspace to that of the patient when performing different types of tasks. Each DOF in the prototype was actuated by an MX-28 Dynamixel Servo capable of delivering 2.5 N·m of torque.

The lack of additional DOFs for the knuckle joints necessitated a slight curvature in the fingers to allow for reliable grasping of objects of varying sizes. The curvature increased the surface area in contact with the object. Additionally, three textured rubber pads were fixed to each finger to increase the friction between the finger and the object. The pads also had a small air bubble behind them in order to add compliance. This preliminary design mainly serves as a proof of concept for wearable finger assisted ADL training of impaired arms. Optimizing finger morphology and attachment configuration, as well as incorporating compliant or underactuated elements [13-17], will improve grasp security and aid patients in more complex tasks. An SR Finger prototype that consists of modular, pneumatically actuated joints and phalanges with variable stiffness is currently being investigated in [18] as an alternative approach.

To control the SR Fingers, the patient's healthy hand is monitored by a sensor glove, and the robotic fingers mimic the open or closed state of the healthy hand. This interface provides an intuitive way for the user to control the robotic fingers. Moreover, the patients can concurrently move the healthy hand and the robot assisted non-functional hand to grasp objects together, which is useful for bimanual tasks that require synchronized grasping.

The simple sensor glove was developed to monitor the pose of the user's healthy hand. It contains three variable capacitance stretch sensors which are attached to the thumb, index, and middle fingers of a wool glove. As the user opens and closes his/her fingers, the change in capacitance of the stretch sensors reflects the degree of finger flexure.

CALIBRATION AND TASK TRAINING

Because hand size can vary widely from patient to patient, the strain measured from the stretch sensors must be calibrated before each use. This is accomplished by prompting the user to first fully open the fingers and then to grasp the object of interest. The strains are measured and recorded as baselines for each of these states. The measurements taken by the sensor glove are continually broadcasted in real time via Bluetooth to the computer which serves as the controller for the robotic fingers.

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The size and shape of the objects typically manipulated by patients in order to perform ADLs can vary. Therefore, a training routine was designed to allow the device to be customized to individual tasks. The position of each robotic finger joint is monitored with a 12 bit, contactless encoder built into each of the Dynamixel servos. The position of each of the joints is recorded and saved for a number of different tasks. Using this routine, if a patient wishes to use the device to manipulate an object that has a non-standard shape or size, a therapist can train the robot by manually moving the SR Fingers through the grasping motion. This grasp can then be repeated by the SR Fingers for the patient during therapy. This task training method allows the device to be utilized for a wide variety of grasping tasks. We also envision that the training mode will be useful in personalizing movements to specific patients. Additionally, the recorded joint trajectory could also be analyzed to aid in the construction of more complex control schemes for future research.

CONTROL SCHEME

The control scheme for the robotic fingers was designed primarily to mimic the state of the patient's healthy hand. However, the SR Fingers were not designed to follow the trajectory of the patient's fingers exactly. Rather, the goal is to maintain an opened or closed posture based on that of the healthy hand. This minimizes unnecessary SR Finger motion and allows the control to be intuitively understood by the patient without extensive training. In order to determine the state of the user's hand, the controller monitors the status of the thumb and middle finger of the healthy hand. A simple algorithm was used in which the SR Fingers move to the closed grasp position when the user closes these two fingers and to the open grasp position when the user opens these two fingers. If the thumb and middle finger are in opposing configuration, the SR Fingers maintain the current configuration in order to minimize the possibility of the SR Fingers changing state unintentionally. This algorithm is shown in the SR Finger Controller Switching block in Fig. 2 where the human finger positions are used to choose a desired joint angle from either the open or closed joint angle references based on the switching limit. Note that the reference values could be adjusted on a per item basis using the task training technique discussed previously. The translational DOF at the base of the SR Fingers was also included in this state change. When the fingers were in the open state, the position of the base would be retracted higher up the user's forearm to avoid unnecessary interference; similarly, when the state was changed to the closed position, the base would translate closer to the wrist to better reach and grasp the object. The exact locations of base positions were customized for each object using the training routine described above.

The position of the fingers was controlled using a PID control scheme to bring each SR Finger joint to the desired position. The gains for the PID controller were tuned to be soft enough to mimic natural movement rhythms and avoid causing discomfort, while simultaneously remaining stiff enough to

respond quickly to the user's movements. When grasping an object, embedded torque controller on board the Dynamixel servos was also used to exert the desired force on the object. Through experimentation, 5 N was found to successfully aid a user in grasping a variety of objects, ranging from soft plastic cups to heavy walkers. Taking into account the 10 cm distance from the grasping point to the motor shaft, a torque set point of 0.5 N·m was used to achieve the desired 5 N force on the object. The embedded torque limiter (Fig. 2) served to limit the output of the PID controller once the goal torque had been reached. This setup allows the PID controller to regulate the trajectory of the SR Fingers before contacting the object. Once contact has been made, the torque limiter's set point determines how much force the fingers are able to apply. Figure 2 shows the entire control scheme: first making use of the user calibration and the pose of the healthy control hand to choose the desired robotic finger posture, and then utilizing a PID position controller and a torque controller to actuate the SR Fingers and complete the grasp.
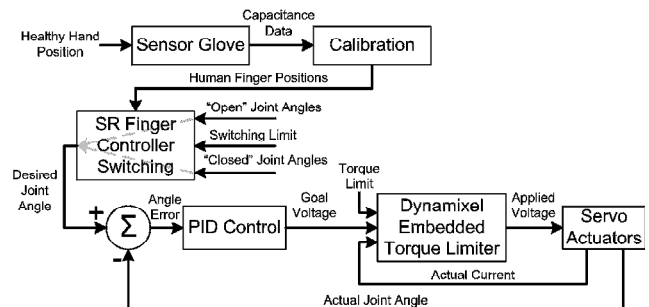

Fig. 2: A schematic of the control setup used to position the SR Fingers based on calibration, training, and the current pose of the user's healthy hand.

While many tasks show a natural synergy between human hands, which allows the user to perform the task with both hands opening and closing in tandem, some tasks do require this synergy to be broken at some stage. Using only this synchronization scheme, the user would need to maintain a closed posture with the healthy hand in order to keep the SR Fingers closed, limiting the freedom of the patient's healthy hand unnecessarily. To solve this problem, an event trigger is included in the controller to signal the switch between different desired robot states. Gestures have long been used to facilitate human-machine interaction [19–21]. Unused or redundant DOFs in the shoulder and foot, for example, are often used to control prosthetic arms [22–24]. In our case, opening only the index finger, while keeping the thumb and other fingers closed, or "pointing", is a distinct gesture that is unlikely to occur unintentionally. Therefore, this gesture was used to trigger a frozen state in which the SR Fingers would stop following the pose of the healthy hand. During ADL training, the user could grasp an object with the SR Fingers, point the index finger to freeze them in the closed posture, use the healthy hand freely without unintentionally releasing the object, and finally, point again to retake control and release the object. For example,
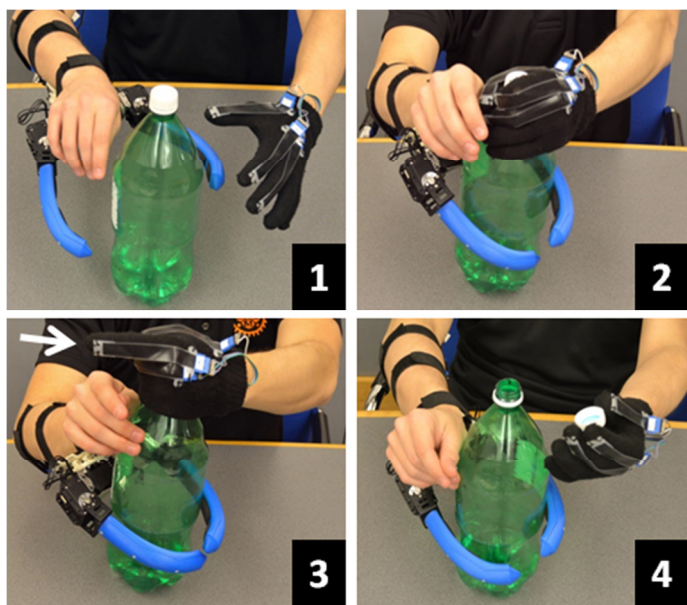
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Fig. 3: Complex tasks require the object to be manipulated after grasping. Here, pointing with the healthy index finger is used as a trigger to toggle between different events. **1)** The bottle is approached by both hands with open postures. The hand wearing the SR Fingers imitates paresis. **2)** When the healthy fingers close around the bottle cap, synchronized grasping control actuates the SR Fingers to grasp the botte as well. **3)** The index finger on the healthy hand is extended (white arrow), commanding the SR Fingers to remain in the latest position. **4)** The healthy fingers are free to twist off the bottle cap while the SR Fingers maintain a stable grasp on the bottle. To release the bottle, the patient can point the index finger again to resume synchronized movement between the healthy hand and the SR Fingers.

Fig. 3 shows this technique being used to open a bottle cap. In Fig. 3.1, the user positions the SR Fingers around the bottle, while the healthy hand controls them to maintain an open posture. In Fig. 3.2, the control hand closes around the top of the bottle, triggering the SR Fingers to grasp the bottle and hold it in place. Figure 3.3 shows the index finger pointing in order to freeze the SR Fingers in place. Finally, in Fig. 3.4, the user unscrews the bottle cap with the healthy hand while the SR Fingers hold the bottle in place. Once this task is completed, the user can simply repeat the pointing gesture to resume coupling between the movement of the healthy hand and the SR Fingers to release the bottle. Device Evaluation

The robotic fingers were tested on healthy subjects to determine if they could complete some bimanual tasks that are frequently used in rehabilitative ADL training. Figure 4 shows the test setup including the sensor glove, SR Finger device, and controller. This setup was used to evaluate the device for a number of tasks.

Some of the tasks were accomplished using natural synchronization alone, which did not require decoupling the SR Fingers from the control hand. For example, one task involved a user attempting to lift two buckets, one in each hand. The subject placed the hand that was being simulated as non-functional onto a bucket's handle, without actually gripping it.
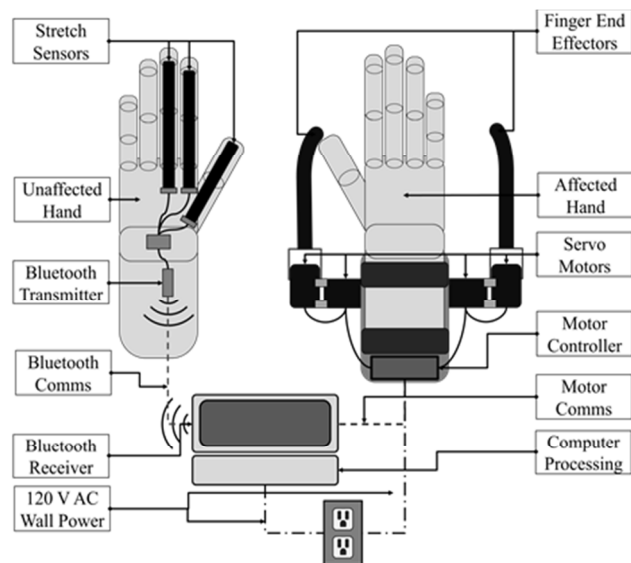

Fig. 4: Schematic of system communication and control setup

When the healthy hand lifted the second bucket, the SR Fingers grasped the first bucket and allowed it to be lifted as well. The user then transferred the buckets to the desired location and released the bucket held in the healthy hand. This caused the robotic fingers to release the second bucket at the new location (Fig. 6.1).

The device was also tested in a pouring task. The goal of the task was to pour liquid from a bottle into a cup while holding both the bottle and the cup. This task normally requires two healthy hands. Using the SR Fingers, the user first placed the simulated non-functional hand next to the cup, just as he would do if it were functional. When the healthy hand was closed on the bottle, the robotic fingers grasped the cup and held it firmly, allowing it to be lifted off of the table. Once the cup had been filled, the test subject released the bottle, consequently causing the SR Fingers to let go of the cup (Fig. 6.2).

Finally, a third application was tested in which the test subject tried grasping and lifting a walker. The subject placed both hands on the walker handles, without using the fingers of the hand that was simulated as non-functional. When the healthy hand closed around the walker handle, the device also closed and gripped the walker handle, allowing the user to successfully walk and steer the walker using only one functioning hand. The test subject then lifted the walker weighing 4.5 kg to simulate avoiding an obstacle or climbing a curb. The robotic fingers were successfully able to maintain their grasp throughout the test. When the task was completed, the user simply opened the healthy hand, which resulted in the SR Fingers releasing their grip on the walker as well (Fig. 6.3).

Other tasks however, require the SR Fingers to be decoupled from the control hand mid-task. These make use of the gesturing technique outlined previously. Three ADLs which require this technique were evaluated. The first was opening a snap-fit container lid which requires holding the container
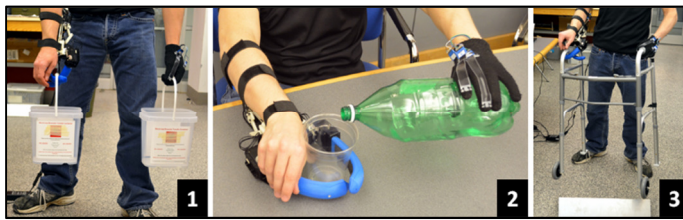
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Fig. 6: Synchronized movement between the healthy hand and the SR Fingers allow the user to perform a variety of ADLs during rehabilitation training. **1)** Two buckets can be lifted, one in each hand, even if one of the hands is not completely functional yet. **2)** The SR Fingers can help secure a cup while the healthy hand pours liquid into the cup. **3)** SR Fingers allow for more flexible steering of a walker and even enable the user to lift the walker off the ground to clear an obstacle.

bottom, while removing the lid. By gesturing to decouple the SR Fingers after they have grasped the container, the user can remove the cover without fear of prematurely releasing the container (Fig. 5.1). Another non-synchronized task was stirring food in a large bowl. The SR Fingers held the bowl in place and the user stirred the contents after gesturing to keep the SR Fingers in the closed grasping posture. Once the stirring was completed, the user pointed at the SR device and then opened the control hand to release the bowl (Fig. 5.2). Finally, a piece of paper towel was ripped from a roll while the SR Fingers held the roll in place. Using gesturing, the user was able to maintain the SR Finger grip on the towel roll while manipulating the paper towel with the healthy hand. Once again, they were able to gesture with the index finger in order to recouple the control hand and release the object (Fig. 5.3).
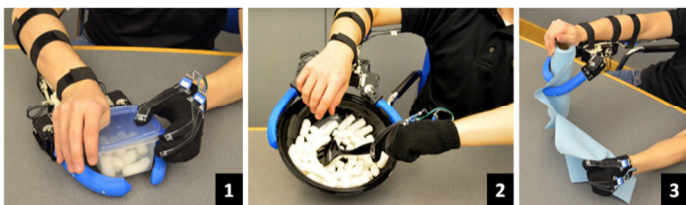

Fig. 5: The index finger pointing tactic enables the user to perform more complex ADLs as the SR Fingers are commanded to maintain their positions. **1)** The SR Fingers hold onto a container as the healthy hand pries open the lid. **2)** The SR Fingers grasp the side of the bowl, allowing the impaired arm to move, shake, and even lift the bowl to assist with mixing the food inside. **3)** The SR Fingers can hold a roll of paper towels in place while the health hand tearing a sheet off.

RESULTS AND DISCUSSION

Our evaluation of the device demonstrated that it could serve as an aid in the completion of some bimanual tasks. However, patients suffering from hemiplegia or hemiparesis can vary over a wide spectrum, ranging from mild weakness and loss of dexterity in the fingers to complete paralysis in the entire left or right side of the body. Since this device requires the patient to actively place it in the approximate position for object grasping, it would not be suitable for use with hemiplegic patients who have no arm function at all. Furthermore, for those patients who do have some arm and

hand functions and are seeking to improve their skills, it would be undesirable to use the device as a crutch which could give the patient a false sense of confidence. Instead, the therapist can use the training mode to modify the amount of assistance the device provides to a level which is appropriate for each individual patient and their current phase of treatment. By choosing a closed SR Finger posture which results in only the amount of assistance the patient needs to complete the task, and not more, the therapist can choose to require the patient to attempt more use of their hand than would be necessary if the hand was used only as a ground for the robotic fingers.

It is also worth noting that the device is not currently capable of assisting in all types of grasps needed to perform the common ADLs. Some tasks, such as buttoning, are simply too dexterous to be performed by this device. Others, such as tying shoelaces, would require more complex control schemes to synchronize the human and robot trajectories. However, there are many bimanual tasks, including those evaluated above, where the ability to grasp and hold an object with the weak hand is sufficient to enable the patient to successfully complete the task.

CONCLUSION AND FUTURE WORK

The prototype device presented in this paper successfully assisted users in completing six bimanual tasks. These simple ADLs are commonly used during rehabilitation training and they are often difficult to accomplish for hemiparetic patients, especially during the early phase of the treatment. With the aid of the robotic fingers, the patients can better perform these tasks and closely simulate the desired motion with the non-functional hand for rehabilitation purposes. The patient can exercise the impaired arm by positioning the SR Fingers next to the object and can attempt to aid in the grasping motion to the extent of their abilities. The tasks will be completed by the robotic fingers even if the patient's fingers are too weak to do so, thus providing the patient with the motivation to attempt these tasks and minimizing the feelings of defeat that may arise when attempting to complete tasks beyond their current capability. This could help the patient to eventually regain the ability to complete these tasks on their own. The patient may benefit in the short term with increased feelings of independence while simultaneously working toward the long term goals of rehabilitation and healing.

Future iterations could refine this design by including force feedback on the robotic fingers to maintain a desired contact force. More advanced torque control may also be incorporated to automatically adapt to object geometry and material properties, enabling more efficient and secure grasps. The device could be further developed by installing an actuated strapping mechanism so that the patient could attach the device with only one hand. Clinical trials will then be necessary in order to gauge the rehabilitation benefits a patient could expect to gain through using this device. Additional opportunities for this device include patient monitored rehabilitation training that can be done at home and direct ADL assistance for those with minimal hand function.

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