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Applications in Hand-Focused Rehabilitation Therapy: A Critical Review of Selected Literature

The purpose of this literature review is to determine the efficacy of various hand-focused applications to stroke rehabilitation. The literature was chosen based on key areas of stroke rehabilitation: assessment metric theory, sensor and control design, engagement, and mobility. By determining how well the applications within the literature achieve their research goals, my project should have better direction in certain future developments it may have.

There are several different methodologies to quantify the motor function of the human hand such as the Fugl-Meyer Assessment (FMA) and the Action Reach Arm Test (ARAT). Such methods do not make clear distinctions between finger strength and individual finger control however. Jing Xu et al. in the Johns Hopkins Department of Neurology have attempted to develop novel metrics for strength and individuation through implementing a custom-built hand evaluation device.[6] Fifty-four patients affected by ischemic stroke and hemiparesis, demographic information of whom is given by Table 1, and fourteen healthy control participants across three medical centers volunteered for five separate visits over a period of fifty-four weeks. The study captured a large and diverse pool of participants from more than one geographic region. This is a positive aspect of the experimental design since it will help the assessment metrics represent the general population of stroke patients better. During each visit, a given participant has both hands fitted into custom keyboard devices shown in Figure 1A, which can track one-dimensional pressing forces from each digit. The participant is presented with a display of finger forces in the form of moving horizontal bars on vertical scales for each digit, depicted in Figure 1B. Desired levels for the strength and individuation tasks were indicated by green bars with a fixed height per trial. Strength, or maximum voluntary contraction force (MVF), was evaluated twice for each digit by having patients depress and maintain a given finger at maximum strength for two seconds. Individuation was evaluated by having each digit reach and maintain one of four sub-MVF target levels for 0.5 seconds, repeating each level four times. Overall strength was averaged over all five digits and normalized into an index metric with respect to the non-paretic hand performance at the end of the study period. In theory, an Index value of 1 corresponded to full recovery. One drawback of the methodology is that it generates a generalized statistic that obscures the different capacities of strength that each digit has. In particular, averaging the strength of the thumb with the other digits seems inappropriate given that the thumb is not a proper finger since it operates on different biomechanical principles. A better calculation could involve different weights for each finger based on their relative strength contribution to the hand. The index for individuation is the negative logarithm of the regression ratio between the active finger force and passive finger enslaving, which is then averaged across all active digits and normalized to end-study non-paretic performance. Although the raw index calculation seemed obtuse and arbitrary upon first glance, the paper authors made an effort to explain each step and justification of the calculation with relevant sources. Although there are perhaps many ways to describe a person's individuation ability, the method that the researchers introduced seemed valid and well-reasoned. Perfectly immobile passive fingers across all possible active digits correspond to a zero-value regression slope and an Individuation Index value of 1. Both indices exhibited the most improvement with the first twelve post-stroke weeks with recovery stabilizing after three to six months. These trends are graphed in Figure 2. The authors also found that the indices were not correlated with age, gender, or handiness for paretic hands. One limitation of the study was that the device only captured a single direction of force for each digit. Given the unique biomechanics of the thumb and possible lateral or lifting motion of the passive fingers during individuation, implementing sensors that capture bidirectional forces in all three dimensions would be an important step forward. In that sense, the multi-axis hand rehabilitation device I am currently working on serves as a successor to that evaluation device. Furthermore, a similar strength and individuation test and interface could serve my project well in evaluating the motor performance of users.

Another important aspect of rehabilitation is the ability to keep stroke patients engaged and consistently changed over the course of their recovery. Jean-Claude Metzger et al. at ETH Zurich explored an adaptive therapy technique to understand the feasibility of maximizing participation and minimizing frustration through careful adjustment of difficulty.[5] In a prior design study, they developed the ReHapticKnob, a 2DOF passive haptic robot that can track the squeezing distance between the thumb and the index finger of a given hand (known as grip aperture) and the rotation of the corresponding forearm (known as pronosupination angle).[4] This device is depicted in the more recent paper in Figure 1B-C. For this particular study, six subacute stroke patients (age is 72.8 ± 12.0 years) with mild upper limb impairment and hemiparesis were selected. The general demographic information of these patients is given in Table 1. Given that the study was a proof of concept, it seems reasonable to have a small sample size to demonstrate feasibility of adaptive difficulty. However, there appeared to be no mention of a control group (e.g. healthy participants) except for developing stimuli steps for robotic assessment. Additionally, there was no mention of which general geographic areas the participants were recruited from besides the clinic location where the study was carried out. For a pilot study, convenience sampling from around that clinic may be justifiable but it should at least be disclosed in the text of the paper. Four days per week, each patient received 45 minutes of neurocognitive therapy utilizing the ReHapticKnob. A given session had three 15-minute exercises selected from seven possible neurocognitive exercises. These exercises evaluated aspects of proprioception of grip aperture and pronosupination, haptic perception of stiffness from grasping and pinching, sensorimotor memory of grip aperture and pronosupination, and sensorimotor coordination through forearm rotation. Before the exercises started, patients also were instructed to complete three robotic assessments to determine the active range of motion, patient-specific difficulty levels, and the initial exercise difficulty. Difficulty for a given exercise was adjusted based on a patient's calculated performance from the last exercise, which in most cases was a percentage of successfully completed trials. All steps of the experimental process are shown in Figure 3. A positive aspect of this article is the inclusion of a tabular image in Figure 2 that contains images and detailed descriptions of the visual feedback on screen for patients, the difficulty levels and design parameters, and the performance metric for each exercise type. Average performance across all sessions with adaptive difficulty was 64%, with the highest average for a given session being 71%, the lowest being 57%, and the overall average in variability being ±21%. This trend is graphed in Figure 5. The team did note this high variability as being a limitation to achieving the goal of the study due to some patients still experiencing high or low difficulty with certain tasks. They suggested improvement to the adaptive algorithm for future research to minimize the variability in performance, which seems reasonable. The researchers demonstrated solid statistical evidence that the pronosupination range of motion, FMA-UE score, and compliance perception improved by the follow-up interview while proprioception worsened then improved over time. A graphical summary of these results is conveyed in Figure 6. Overall, the team conveys strong arguments that their methodology keeps users engaged at a consistent performance with increasing difficulty and improving motor ability. Three things that they should focus in the future are evaluating the other three digits of the hand, expanding the demographic of the subject pool, and fine-tuning their adaptive difficulty algorithm. My project could benefit from utilizing its own adaptive difficulty adjustment to keep users engaged while maintaining force levels for strength and individuation. Furthermore, the mechanical actuator adjustment implemented in both this ReHapticKnob system and my project allows the devices to accommodate a variety of possible hand sizes from stroke-affected patients.

Passive and active haptic devices usually possess positive aspects of rehabilitation that the other category is unable to achieve. For example, active robotics can control the level of force for patients, but are often bulky and have limited range; passive robotics are more compact and are associated with larger ranges of motion, but they possess no way to control the motions of the user's hand when needed. To maximize the positive characteristics and minimize the negative aspects within a single package for patients, Ludovic Dovat et al. have developed a hybrid device known as the HandCARE rehabilitation system.[1] The device, depicted in Figures 1 and 3, secures the fingers of patients to cables guided by pulleys, and is back-drivable to support opposing motions. To reduce force bias from non-collinear forces, differential sensing of cable tension is implemented through the use of a three-pulley system and 2 N force sensors positioned orthogonally to the cable, as shown in Figure 6. A clutch subsystem depicted in Figure 5 can modify the movement behavior of all five fingers from a single actuator. Potential materials for the cable included polyester, carbon-fiber-reinforced polyester, polyethylene fiber, and steel. 0.5 mm-thick steel was chosen since presumably it had the best compromise for compliance, pulley friction, breaking strength, and creep. The pulleys are made from POM and the cogwheels are made from steel to maximize fatigue durability. However, the authors do not provide specific statistical information about their selection process, which is a notable drawback of the paper since their reasoning is difficult to verify. Three possible movement modes exist for a given finger: a free mode where the cable cogwheel is disengaged and the finger can drive the cable without restriction, an active mode where the cogwheel is engaged with a torque-generating motor/encoder subsystem, and a fixed mode where the cogwheel is fixed to induce cable blocking. Five linear paths of 8 cm each forms the workspace of the user's hand, allowing anywhere from 1.5 to 19 cm between the thumb and opposing fingers. Maximum force generation from the motor is 15 N. To determine these characteristics, the authors recruited eight healthy participants and five right-handed chronic stroke patients for a brief measurement study. The authors measured the orientations and lengths of fingertips for each individual, and concluded that post-stroke subjects had different orientations and trajectory amplitudes, as shown in Figure 2, due to limited finger abduction. From general observation of their graphical data and from common sense, this claim seems reasonable. However, there is a lack of statistical testing to explicitly support their claim, which is a notable drawback of the paper. Besides the inability to fully close the hand, the actuation characteristics seem appropriate for reading and controlling a human hand, a positive aspect of the system. Sampling of the motor encoder occurs at 100 Hz, while sampling of the cable force sensors occurs at 1000 Hz; any needed active mode commands are sent back to the motor at 100Hz. The authors justify the choice of relatively low motor-associated frequencies by stating that human movement occupies a bandwidth of 2 to 7 Hz, which seems reasonable. A mechanical stop for each digit and an overall emergency switch were implemented to ensure the safety of the user, the emphasis of which is a positive highlight of the article. Distal control devices such as the HandCARE system are the most related mechanically to my project due to the emphasis on actuation through the fingertips. The individual fingertip sensing of forces is an integral part of my own project, which necessitates careful calibration as well to ensure voltage signals from the transducers represent the user's forces accurately.

Portability and home use are a vital goal for hand-focused rehabilitation. N.S.K. Ho et al. at the Hong Kong Polytechnic University have developed a training exoskeleton for a patient's hand that detects intention from EMG signals in the impaired hand.[2] Figure 1 shows different general views of the device. The hand module utilizes a single linear actuator for each digit with two degrees of freedom as shown in Figure 2. Although the finger assemblies are identical, they can be fitted for each finger length. EMG signals are sampled at 1 kHz from the abductor pollicis brevis muscle group and the extensor digitorum group; hand closing is controlled through the former while hand opening would be controlled through the latter. These signals are depicted as transient graphs not unlike those shown in Figure 5. The hand device weighs 500 grams, and a battery and wireless transmitter shown in Figure 3 were utilized to make the system portable and easy for patients to carry around. Despite the emphasis on portability, there is an absence of information on the capacity of the battery or how much power the system draws. To validate the system, eight chronic stroke patients volunteered for twenty task training sessions with three to five sessions per week. Demographic information is given in Table 1. There was no indication of where patients were generally recruited from, so it is difficult to determine if sampling was done through convenience or not. As a preliminary development study, convenience sampling is acceptable, but it should be disclosed in the article text. Also, there was no particular control group stated and data analysis later in the article compared only post-study and pre-study assessment scores of stroke-affected participants. This may also be reasonable given the preliminary and development-oriented nature of the study, but later clinical studies with the device should involve a larger participant pool and introduce healthy participants as a control. The team did perform a later study with a stronger focus on EMG activation levels that incorporated a larger sample group of stroke patients (n = 10), although they used the bare paretic hand as a control for t-tests.[3] During a given session, subjects were instructed to complete two 10-minute sets of training tasks with 5 minutes of rest in-between. Patients can close or open the hand by exceeding 20% of the patient-specific maximum voluntary contraction EMG threshold for a given muscle group. The first task was to move a foam block 50 centimeters horizontally, whereas the second task was to move the block 20 centimeters vertically, the experimental setup of which is shown in Figure 6. Improvements in motor function before and after the trial period were assessed using FMA and ARAT. FMA scores for the shoulder and elbow changed from 21.50±2.59 to 28.00±7.40, FMA scores for the wrist and hand changed from 7.83±5.11 to 11.83±5.85, and ARAT scores improved from 21.833±8.66 to 29.67±9.17. All score changes were statistically significant through paired t-test analysis, demonstrated in Table 2. A potential future direction that the team could take is to increase the number of participants in the study and to provide explicit evidence that powering the system via a battery is feasible for a reasonable period of time. Indeed, mobility has become an important part of my own project, as its home use is feasible thanks to its light weight and USB power/data capabilities. Plus, the concept of using Velcro to secure the hand can be applied to my own project by securing the wrist brace with Velcro.

These studies provide valuable insight for my own project as they provide useful information regarding the representation of motor performance, the accurate reading of user-transmitted forces, the proper scaling of difficulty for engagement, and mobility. From recognizing the advancements and learning from oversights of these various authors, I can ensure that my project should do its best to assist stroke-affected patients and to realize their improved recovery of upper-limb function.

Citations:

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