Tele-Rehabilitation using the Rutgers Master II glove following Carpal Tunnel Release surgery

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***Abstract*— Carpal tunnel syndrome is caused by the compression of the median nerve as it transits the carpal tunnel, with an incidence of about 1% of the population. If surgery is needed, the treatment involves decompression of the median nerve followed sometimes by musculo-skeletal outpatient rehabilitation. This paper presents results of pilot clinical trials in which the Rutgers Masters II haptic glove was tested on five subjects, who were two weeks post hand surgery. Subjects trained for 13 sessions, 30 minutes per session, three sessions per week, and had no conventional outpatient therapy. Computerized measures of performance showed group effects in hand mechanical energy (1,200% for the virtual ball squeezing and Digikey exercises and 600% for the power putty). Improvement in their hand function was also observed (a 38% reduction in virtual pegboard errors, and 70% fewer virtual hand ball errors). Clinical strength measures showed increases in grip (by up to 150%) and key pinch (up to 46%) strength in three of the subjects, while two subjects had decreased strength following the study. However, all five subjects improved in their tip pinch strength of their affected hand (between 20% and 267%). When asked whether they would recommend the VR exercises to others, four subjects very strongly agreed and one strongly agreed that they would.**

I. Introduction

THE Carpal Tunnel is the conduit by which finger flexor tendons are allowed to translate during grasp (Figure 1*a*, [1]). The same anatomy is shared by the median nerve, which occasionally becomes compressed within the carpal tunnel, causing numbness and tingling of the thumb, index, middle and ring fingers (Figure 1*b*). The incidence of Carpal Tunnel is about 1% of the population, with higher incidence for professions where repetitive hand motions occur. Conventional treatment includes medication, splints to immobilize the wrist, or surgery to "decompress" the median nerve. Rehabilitation interventions post-surgery concentrate on regaining finger range of motion, grip strength and relieving sensitivity in the surgical area. The aim is for the patient to be able to use their affected hand in activities of daily living and in their work, without experiencing the troublesome symptoms of numbness and tingling in their fingers. The improvement in hand strength is typically gauged by the patient's subjective responses and objectively, by measuring static grip strength and pinch strength using standardized instruments (hand-held dynamometer, and pinchmeter). A Semmens-Weinstein test [2] is used to gauge changes in sensation. Fine motor and functional task completion are also objective measures of improvement.

The use of virtual reality (VR) in physical therapy has focused mostly on the post-stroke population. Less effort has targeted patients with musculo-skeletal deficits, whether from fractures, arthritis, or surgery (see [3] for a review). Virtual Reality address the needs of sub-acute musculo-skeletal training by providing virtual games designed to motivate and engage the patients in a period of intensive exercises. Sveistrup et al. [4] report on the use of the Interactive Rehabilitation Exercise System (IREX, Ottawa, Canada) for the training of patients with chronic frozen shoulder. Virtual Reality-based rehabilitation was provided in the form of soccer games aimed at eliciting shoulder flexion, abduction and rotation. Two case studies showed about 20% improvement following six weeks of training (three sessions/week). Deutsch et al. [5] used the Rutgers Ankle robot and VR to train three patients with musculo-skeletal impairments to their ankle. Patients sat in front of a PC and were asked to pilot a virtual airplane with their ankle, passing through hoops against the robot resistance. All three patients improved in various computerized measures (ankle torque, ankle control, or ankle range of motion).

Our group pioneered the use of VR in musculo-skeletal rehabilitation for the upper extremity [6] in a precursor study to the research reported here. A patient post Carpal Tunnel release surgery trained at Stanford University with remote monitoring from Rutgers University [7]. The subject improved during a 4-week outpatient training using an earlier version of the Rutgers Master glove. Subsequently both hardware and software were refined and a series of five case studies were done in 2005 at Integris Healthcare (Oklahoma City), again with remote monitoring from Rutgers University. Section 2 of this paper describes the experimental system used in these trials. The experimental protocol and data on the subjects participating in the study are given in Section 3. Section 4 describes the computerized, clinical and subjective evaluation outcomes, looking at group effects and subject-specific data. Section 5 concludes this paper.

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II. EXPERIMENTAL SYSTEM

A. Hardware

The VR-rehabilitation system used in this study consists of a PC (Pentium III dual processor), a 3D tracker (Polhemus Fastrak [8]), left- and right-hand Rutgers Master II gloves (Figure 2*a*) with their control box, a small and quiet compressor (50 dB) and a Cannon pan-tilt-zoom (PTZ) camera controlled over the Internet. The haptic gloves are used to measure in real time the thumb, index, middle and ring fingertip positions vs. the palm. Custom actuators resist flexion (up to 16 N) or assist extension to the neutral hand configuration. Each actuator is controlled independently, such that some fingers may be resisted, while others are assisted. High-friction finger attachments for each piston, together with the Velcro used to position a palm plate for "grounding" the mechanical forces, obviate the need for a separate supporting glove. The tracker is placed on the dorsum of the hand and is used to measure the patient's wrist movements 120 times/second. A remote therapist expert looks at the PTZ camera images through a web browser, communicates with the local therapist over the phone and has access to the patient treatment/history through a web portal.

B. Virtual Reality Exercises

Five therapeutic games were created based on the advice provided by the clinician researchers at Stanford collaborating in this study. The simulations were programmed using WorldToolKit [9] running in the Windows 2000 operating system. The first three exercises ("ball squeezing," "power putty" and "digikey") train the hand impairments (finger strengthening). The other two simulations ("peg board" and "hand ball") are more complex and aim at improving the whole arm function (hand-eye coordination, active shoulder range of motion, precision placement of objects). As can be seen in Figure 2*b-f*, all exercises have a similar graphical user interface (GUI). This GUI mediates the therapist's input into the exercises and provides real-time performance feedback to both therapist and patient. At the bottom of the screen are graphical buttons to "start," "pause," or "quit" the exercise, as well as a hand icon indicating which hand (left or right) is being trained. Also at the bottom of the GUI is a "recalibrate" button, which allows the patient to recalibrate the glove in-between exercises,

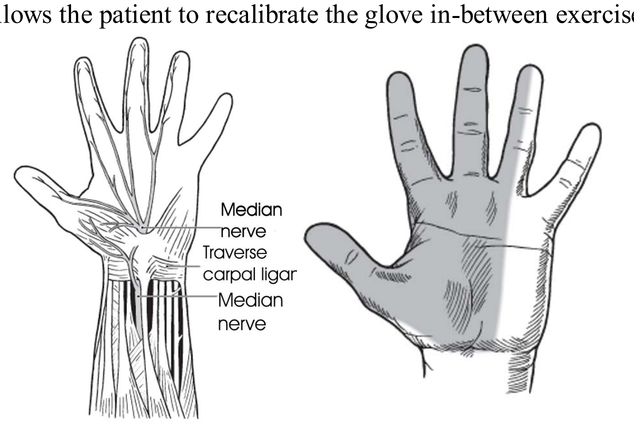

Fig 1. Carpal Tunnel syndrome: a) median nerve in the hand; b) numbness area of the palm [1].

or as needed. Performance feedback is provided either graphically or numerically. For the finger impairment exercises, four bar graphs at the top left corner of the screen, visualize in real time, the level of individual finger forces. For all five exercises the bottom of the screen displays numerically the goal set by the therapist, and the patient's performance. If the patient completes the exercise in the allowed time a congratulatory sound is displayed, otherwise the simulation slowly stops the exercise and exits automatically.

Virtual ball squeezing is designed to strengthen the patient's finger flexion movement, and consists of a virtual elastic ball that the patient grasps with a virtual hand. The goal is to "squeeze" the virtual ball a prescribed number of times, within a given time allotment. The exercise difficulty varies with the ball stiffness (no resistance – level 0, soft, medium and hard-level 3). The color of the virtual ball changes to correspond with the difficulty level. The "finger forces" bar graph is initially a simple horizontal line for each finger. When the forces in a finger reach or exceed the force threshold set by the difficulty level, the bar will turn solid. A squeeze is recorded only when all four fingers are providing forces at or above the difficulty level set for the exercise. The same approach is taken for the power putty and digikey exercises (described below).

Virtual power putty simulation exercises only the thumb and index finger, which plastically deform the power putty. In order to maximize finger excursion, the power putty is modeled as a sequence of individually deformable segments. After the target segment is squeezed, it translates out of the way, being replaced by a new non-deformed putty segment. Similar to the previous exercise, the patient is required to squeeze the virtual putty beyond a threshold determined be the putty's fluid resistance for that difficulty level (0- no resistance to hard-level 3).

The virtual Digikey is modeled after the well-known Digikey therapeutic device, which looks like a trumpet keyboard with springs. Due to the Rutgers Master II characteristics our simulation has a modified Digikey to allow thumb training instead of 5th digit . There are five virtual Digikeys, each with a different resistance level, corresponding to the color code legend at the bottom of the GUI. The patient is asked to squeeze and release the Digikey repeatedly, to match the goal displayed on the screen.

The virtual pegboard is also modeled after a well-known therapeutic device used in patient evaluation and training of fine movements and hand-eye coordination. The simulation consists of nine pegs (cylinders) and a board with a nine-hole matrix, which the patient needs to fill, one peg at-a-time. The level of difficulty (1-"novice," 2-"medium," and 3-"expert") is set by the size of the holes, with tighter tolerances requiring higher skill. The goal of this exercise is to place a peg in each of the nine holes within the allowed amount of time. When a peg is placed above an unfilled hole, it will change color to green, and is released to fill the hole. An error is recorded if he patient drops the peg outside a hole, or when a grasped peg, or when a grasped peg collides with another peg, the peg.

The virtual handball game asks patients to throw a virtual ball so it hits in the white target zone on a virtual wall (Figure 2*f*). The ball will then bounce off the wall and needs to be caught by the patient before it hits the floor twice. The initial speed of the ball determines the level of difficulty (an orange “slow” ball, or a red “fast” ball). The GUI for this exercise has an additional button, to “reset” the ball to the initial position, bouncing in the center of the room. A reset will be recorded as an event to the database. An error occurs if the patient fails to throw the ball into the target zone, or when the ball bounces two or more times after hitting this zone, before being caught by the patient.

B. Clinical Database

While patients are exercising, the simulation transparently measures and stores several parameters in the clinical database. The data is stored first locally on the PC running the VR exercises. Subsequently, data are uploaded every night to the remote server running the Oracle graphing routine. For the trials reported here, the PC was in Oklahoma City, while the Oracle server ran on a PC at Rutgers University (approximately 2,100 km away). Patient data from the exercises are stored at “low level” (detailing finger specific real-time movements, or forces) or “high level” (for averages of exercise completion time, number of grasps, mechanical work, number of errors). A web-accessible password-protected database portal allows local or remote clinicians to follow the patients’ progress over time. For each subject and each exercise it is possible to request variable-specific history graphs. The bottom axis plots the session dates, while the top horizontal axis shows the exercise difficulty for those sessions. It is thus easy to see how the subject progresses from level to level over time, without having to be next to the patient.

III EXPERIMENTAL PROTOCOL

The five exercises described above form the basis of the musculo-skeletal post surgical rehabilitation protocol for a five-week (13 sessions) training intervention. The difficulty level is progressing based on the type of exercises, their number of repetitions, as well as the difficulty level of each type of exercise. During the first two sessions patients perform a fixed sequence of ball squeezing (no resistance-level 0, 20 grasps over 5 min), power putty (no resistance-level 0, 20 grasps over 5 min), Digikey (level 1 resistance, 20 grasps over 5 min). Starting with Session 3 the sequence remains the same, but the difficulty is increased for ball squeezing (level 1 - “soft,” 30 grasps, 5 min), power putty (level 1 -“soft,” 30 grasps, 5 min), Digikey (resistance level 2, 30 grasps, 5 min). In session 7 the peg board and hand ball games are added, resistance is increased to level 2 “medium” for the ball squeezing and power putty exercises, the Digikey is producing level 3 forces, and the pegboard tolerances are tightened to level 2- “medium” in session 9. In session 12 the difficulty is increased further (ball squeezing, power putty are at level 3 forces, Digikey at level 4 forces, and the pegboard is performed at the tightest tolerances – level 3 “expert”).

The sequence of exercises is pre-programmed into the PC, such that each exercise will be started automatically, at the

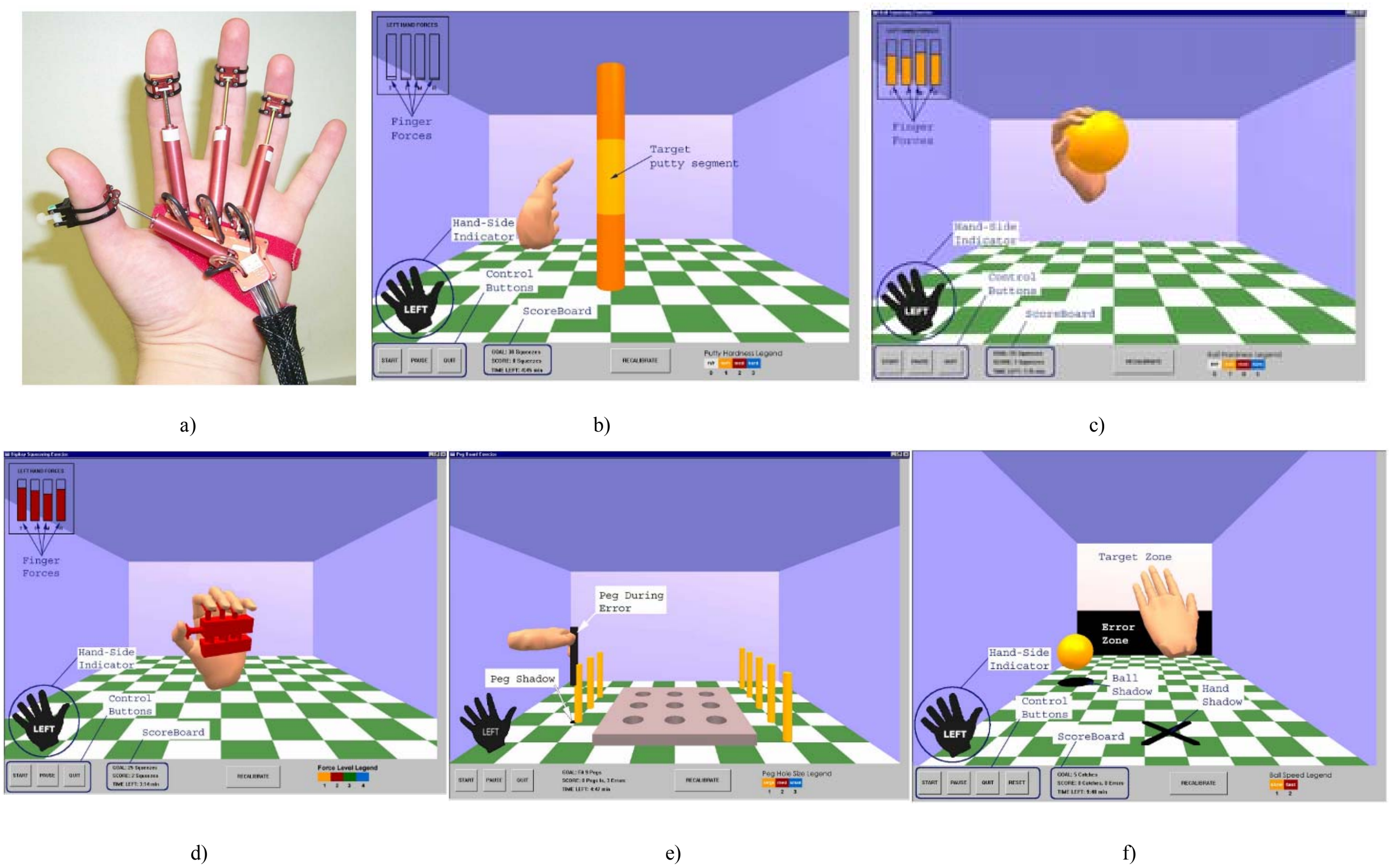

Fig. 2: Virtual Reality system: a) Rutgers Master II glove; b) rubber ball squeezing; c) power putty; c) Digikey; e) peg board filling; f) hand-ball exercise. © Rutgers University.

appropriate level of difficulty and in the correct order for the particular week of training. To allow a certain level of flexibility for a specific patient's impairment level and daily physical condition, a "Session Configuration" GUI is added. For each patient the GUI allows the therapist to deviate from the preset order by changing the default settings (completion time, number of squeezes, pegboard tolerance level, number of catches for the handball game). The same software allows the therapist to add/remove one or several exercises from that session.

The protocol was submitted for review to the Institutional Review Board of Rutgers University and the Internal Review Committee of Integris Health and was approved. Subsequently a collaborating orthopedic surgeon randomly recruited eight subjects via direct referral. The admission criteria to the study were: 1) subjects needed to be post a first-time carpal tunnel surgery of their affected hand; and 2) they had to have no other prior trauma, injuries or surgeries to their affected wrist/hand. Each subject was instructed on the use of the Rutgers Master II glove and virtual reality simulations. They subsequently signed the consent to participate in this study and underwent pre-surgical testing (hand dynamometer; pinchmeter and Semmes-Weinsten testing). The study began 13 days post-surgery if their wound had healed. Of the recruited subjects, three withdrew from the study (two prior to starting the VR therapy) and five completed it. The age range for the subjects that completed the study was 39 to 67, with a mean of 59 years. Since one subject had a pacemaker there was a safety concern with interference from the tracker magnetic fields. Engineers with both the tracker and the pace maker manufacturers were consulted and advised that there were no indications of such interference. That patient completed the study without incident. Following completion of the study, subjects were again tested clinically using the same methods as the pre-surgical testing. They also had to fill subjective evaluation questionnaires rating the system.

IV. Results and Discussion

A Computerized measures of performance

Table 1 shows group averages for a subset of the computerized variables stored during the VR-based training. For the three exercises that trained at the impairment level (ball squeezing, power putty and DigiKey) the variables are trial completion time (in seconds) and mechanical energy (Joules) as a function of difficulty level. For the remaining two exercises (peg board and ball game), which trained function, the variables are trial completion time and number of errors as a function of difficulty level.

The computerized variables are tabulated for the group performance measured in the first session (1) (session 3 for ball squeezing and power putty; session 7 for the ball game) and the last session of training (session 13). A further caveat is the completion time of impairment-level trials, which is shown normalized for Session 13. This is due to the fact that the number of grasps changed from 20 (session 1) to 30 (sessions 7 and thereafter). It can be seen in Table 1 that the patients as a group were able to expand substantially more energy at the end of training and do so at a high level of resistance from the haptic glove. This was true for all impairment-level trials. Expanded energy during the DigiKey exercises, for example, increased by 1200% for the subjects as a group, while the time to complete the trial decreased

TABLE I GROUP PERFORMANCE VARIABLES MEASURED BY THE COMPUTER

Exercise	**Group average (Session 1)**			**Group average (Session 13)**		
Variable	**Time (sec)**	**Energy (J)**	**Diffi-culty**	**Time (sec)**	**Energy (J)**	**Diffi-culty**
Ball squee-zing*	71	2	1	37 (-39%)	24 (1200%)	3
Power putty*	102	0.5	1	61 (-40%)	3 (600%)	3
DigiKey	54	1	1	39 (-28%)	12 (1200%)	4
Variable	**Time (sec)**	**Errors**	**Level**	**Time (sec)**	**Errors**	**Level**
Peg Board	238	5.8	1	247 (4%)	3.6 (-38%)	3
Hand ball (starts session 7)	271	9.8	1	180 (-32%)	2.9 (-70%)	1

*Session 3

(-28%). Thus the subjects' hand mechanical power improved too (their hand ability to expand energy in a given amount of time). The group took substantially longer to complete the functional training trials, but had a significant drop in errors (-38% for peg board and –70% for the hand ball game). This shows that the group improved in hand fine motor control and hand-eye coordination, despite an increase in the level of difficulty of the peg board game. The hand ball game, which started about midway through the therapy, was kept at a constant difficulty level, nevertheless the group showed substantial hand-eye coordination improvement. Note that such functional outcomes are not captured in clinical "static" strength measures detailed below, and represent a clear advantage of the VR system over conventional evaluation approaches. A further advantage (not described here due to lack of space) is the ability to gauge progress (in terms of strength, endurance, etc.) on a finger-specific level, and with high time granularity. In comparison to conventional post-surgical carpal tunnel release surgery, only one of these patients would have been referred to Physical Therapy for follow up treatment. According to the referring hand surgeon, Dr Sean O'Brian only about 10 to 15 % of his patients are referred to Physical Hand Therapy.

B Clinical Outcomes

Table 2 presents the strength subset of the pre- and post-VR therapy clinical measures. Data are shown for the affected hand, for grip and pinch strengths, as well as the subjects' % increase/decrease in such strength. Data shows substantially less clinical outcome uniformity among the group. Three of the subjects (60 %) increased their grip (up to 150%), key pinch strength (up to 46%). Two subjects (40 %) had a substantial reduction in their hand grip strength (up to –31%) and key pinch (up to –395) during the study. The logical explanation is subject 2 was elderly and not using his hand at home, and subject was continuing to work but admittedly neglecting to use her hand due to pain and swelling. Remarkably, all subjects improved in their tip pinch strength (between 20% and 267%).

TABLE II

CLINICAL MEASURES OF SUBJECTS" STRENGTH FOR THE AFFECTED HAND (PRE AND POST INTERVENTION)

Subject	Grip strength (lbf)		Key Pinch Strength (lbf)		Tip Pinch Strength (lbf)	
	Pre	Post	Pre	Post	Pre	Post
2	37	69	13	16	10	12
Difference (%)	32(86%)		3(23%)		2(20%)	
3	80	70	18	11	20	26
Difference (%)	-10(-12%)		-7(-39%)		6(30%)	
4	10	25	3.5	4.5	1.5	5.5
Difference (%)	15(150%)		1(28%)		4(267%)	
5	60	90	13	18	7	12
Difference (%)	30(50%)		6(46%)		5(71%)	
8	65	45	18	13	11	15
Difference (%)	-20(-31%)		-5(-28%)		4(36%)	

C Subjective Evaluation

The *perceived exercise difficulty* was rated by subjects on a 5-step scale: no difficulty (1), mild difficulty (2), moderate difficulty (3), very difficult to perform (4) and unable to perform (5). The overall VR simulations were rated at a 1.6 difficulty, meaning that that the subject group felt it had no-to-mild difficulty when performing the exercises. The subjects had no perceived difficulty doing the impairment-level training: ball squeezing (1) and power putty (1), DigiKey (1.6). As expected, the exercises training function were perceived as more difficult (hand ball – difficulty 2 and peg board – difficulty 2.4). One subject found the pegboard very difficult, and had to have support of the upper extremity and elbow at a proper height to complete the task. Another subject had no experience with video games, the Internet, nor had any sports or ball playing experience in his lifetime. Thus this subject had more difficulty with hand-eye coordination activities and quick movements that involved the entire upper extremity.

The subjects were split in their subjective judgment of *most and least beneficial exercises*. Interestingly, the functional training exercises, which were perceived as more difficult, also received the most votes for being more beneficial (peg board – 2 votes, handball game – 1 vote). Other subjects perceived those same exercises as *least* beneficial (peg board – 2 votes, handball game – 1 vote).

A couple of the subjects experienced some shoulder pain with all of the exercises. The subjects were asked to rate their *level of pain* prior to, during, and after the VR therapy, on a scale of 0 (no pain) to 10 (could not perform the exercise due to excessive pain). Two subjects reported having moderate pain prior to the start of therapy (one subject rated it at 2, one at 3). The perceived pain level went up during therapy with two subjects reporting the pain level at 2, one at 4 and one at 5. Following training, the pain level diminished (two subject had no pain, two reported it at level 2 and one at level 4). This mild-to-moderated pain did not prevent the subjects from completing their therapy.

When asked whether they *would recommend the VR exercises to others*, four subjects very strongly agreed and one strongly agreed that they would. This shows a very positive overall rating from the subjects that completed the study.

V. CONCLUSIONS AND FUTURE WORK

The study shows that post-surgery patients' hand strength does improve with VR exercises, in the absence of conventional outpatient clinic therapy. Results also show that repeated practice results in improved function (as measured by the computer). The subjective evaluation of the system was positive, indicating good acceptance and perceived usefulness by the patients. While in this pilot study the therapist was co-located and assisted the patient, such acceptance bodes well for future scenarios where the therapist will be remote. The Rutgers Master II may then be used in conjunction with tele-rehabilitation settings, where local therapist expertise or clinics are lacking [10]. Newer generation of therapists, and patients, which have grown up with computers and video games will also be more accepting of the technology this study has tested.

Future research with the Rutgers Master glove will focus on improved ruggedness, increased number of degrees of freedom, and extension to other patient populations (such a stroke, head injury and reattachment). This will address the needs of rural patients who need long interventions (months to years).

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