ORIGINAL ARTICLE

In-Home Virtual Reality Videogame Telerehabilitation in Adolescents With Hemiplegic Cerebral Palsy

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Objective: To investigate whether in-home remotely monitored virtual reality videogame-based telerehabilitation in adolescents with hemiplegic cerebral palsy can improve hand function and forearm bone health, and demonstrate alterations in motor circuitry activation.

Design: A 3-month proof-of-concept pilot study.

Setting: Virtual reality videogame-based rehabilitation systems were installed in the homes of 3 participants and networked via secure Internet connections to the collaborating engineering school and children's hospital.

Participants: Adolescents (N=3) with severe hemiplegic cerebral palsy.

Intervention: Participants were asked to exercise the plegic hand 30 minutes a day, 5 days a week using a sensor glove fitted to the plegic hand and attached to a remotely monitored videogame console installed in their home. Games were custom developed, focused on finger movement, and included a screen avatar of the hand.

Main Outcome Measures: Standardized occupational therapy assessments, remote assessment of finger range of motion (ROM) based on sensor glove readings, assessment of plegic forearm bone health with dual-energy x-ray absorptiometry (DXA) and peripheral quantitative computed tomography (pQCT), and functional magnetic resonance imaging (fMRI) of hand grip task.

Results: All 3 adolescents showed improved function of the plegic hand on occupational therapy testing, including increased ability to lift objects, and improved finger ROM based on remote measurements. The 2 adolescents who were most compliant showed improvements in radial bone mineral content and area in the plegic arm. For all 3 adolescents, fMRI during grip task contrasting the plegic and nonplegic hand showed expanded spatial extent of activation at posttreatment relative to baseline in brain motor circuitry (eg, primary motor cortex and cerebellum).

Conclusions: Use of remotely monitored virtual reality videogame telerehabilitation appears to produce improved hand function and forearm bone health (as measured by DXA and pQCT) in adolescents with chronic disability who practice regularly. Improved hand function appears to be reflected in functional brain changes.

Key Words: Cerebral palsy; Child; Fiber optic technology; Hand; Hemiplegia; Internet; Perinatal care; Rehabilitation; Stroke; Video games.

USE OF BOTH HANDS is important for most activities of daily living. However, many U.S. children with chronic hemiplegia have limited access to ongoing occupational therapy past the age of 3 years, when free in-home occupational therapy from First Steps programs stops.[1-4] After age 3, occupational therapy may decrease from 1 hour a week through First Steps to 30 minutes or less a month in school. Many health insurance plans are reluctant to cover ongoing therapy. It is difficult to pay for occupational therapy out-of-pocket and take time off from work to take children to therapy sessions (oral personal communications,

List of Abbreviations

BMC	bone mineral content
CIMT	constraint-induced movement therapy
DXA	dual-energy x-ray absorptiometry
FA	flip angle
fMRI	functional magnetic resonance imaging
FOV	field of view
LSC	least significant change
MP-RAGE	magnetization prepared rapid acquisition gradient echo
MRI	magnetic resonance imaging
fMRI	functional magnetic resonance imaging
NEX	number of excitations
pQCT	peripheral quantitative computed tomography
ROM	range of motion
TE	echo time
TMS	transcranial magnetic stimulation
TR	repetition time
VR	virtual reality

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A commercial party having a direct financial interest in the results of the research supporting this article has conferred or will confer a financial benefit on the author or one or more of the authors. Golomb and Burdea have filed a patent application on principles incorporated in this system.

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patient families, Riley Perinatal Stroke clinic). The long-term outlook for these children is bleak—they are left to struggle not only with impaired hand function but also deficit bone health. Children with severe hemiplegia often have thinner bones and decreased bone density in their plegic limbs, placing them at risk for low-trauma fractures.[5]

Previous rehabilitation studies addressing upper limb function in children with cerebral palsy have tried VR videogames in a clinical setting, off-the-shelf videogames, CIMT, TMS, and robotic therapy. Some studies have modified commercially available VR videogames[6] in a clinical setting or used off-the-shelf systems that could be used in the home.[7,8] However, children who live in remote areas would have difficulty accessing systems that must be used in the clinic, and off-the-shelf systems are geared towards children with normal motor function, which can be frustrating for those with more severe impairments. Good results have been reported with CIMT for hemiplegia in children[9-11] and adults,[12,13] but many of these studies excluded patients with the most severe impairments. CIMT trials have excluded patients who did not have at least 20° of active wrist extension,[12,14] had excessive spasticity,[15] had had orthopedic surgery on their affected arm, or seizures.[14] Contralesional TMS shows promise, but few centers are equipped to perform TMS, and children with epilepsy were excluded from the pilot study.[16] Robotic therapy (use of robots to provide therapy) has shown promise in both children[17,18] and adults,[19] but is expensive and not designed for home use.

Our goal was to develop a rehabilitation system accessible even to people living in rural areas, inclusive of the most disabled and those with comorbidities such as epilepsy, and with the potential to become inexpensive with further development. The objective of this study was to provide proof-of-concept evidence that in-home remotely monitored VR videogame telerehabilitation using a sensing glove fitted to the plegic hand could improve hand function and forearm bone health. We used fMRI to investigate alterations in engagement of relevant motor circuitry as reflected by changes in fMRI brain activation patterns during motor tasks.

METHODS

Participants

This was a proof-of-concept pilot study of 3 adolescents with severe right hemiplegic cerebral palsy affecting the arm and hand more than the leg. Subjects 1 and 3 were boys aged 13 and 15 years who both had perinatal stroke in the left middle cerebral artery territory. Subject 1 had perinatal stroke with delayed diagnosis (presumed perinatal stroke), and subject 3 had perinatal stroke with neonatal diagnosis.[20] Both boys also had seizures that were well controlled with oxcarbazepine. Subject 2, a 15-year-old girl, had intraventricular hemorrhage secondary to premature birth at 32 weeks. All 3 subjects had extensive perinatal injury to traditional motor pathways (fig 1). All 3 had undergone multiple tendon surgeries in the right arm between the ages of 3 and 14 years (none had surgery in the year before study onset) and had received botulinum toxin injections to spastic muscles in the right arm (none received botulinum injections in the 6mo before study onset). They all had mirror movements. None were receiving occupational therapy at the time of enrollment. All 3 adolescents were enrolled in age-appropriate classes in regular public schools; 1 did receive some extra help for mild learning issues. Participants and their parents/legal guardians provided written informed consent/assent consistent with a study protocol approved by the institutional review boards of both Indiana University School of Medicine and Rutgers University.

Intervention

Partial technical details of the intervention technique have been published previously.[21] A videogame system that included a 5DT 5 Ultra Glove[a] and a PlayStation3 game console[b] was installed in each participant's home (fig 2). Each system was networked with both Riley Hospital and Rutgers University Tele-Rehabilitation Institute through a DSL (digital subscriber line) modem/router; similar systems were set up at Riley and Rutgers for testing,

Fig 1. Coronal MP-RAGE images demonstrating degree of structural abnormality. (A) Subject 1. (B) Subject 2. (C) Subject 3. Subjects 1 and 3 both had perinatal strokes in the left middle cerebral artery territory. Subject 2 had a left intraventricular hemorrhage due to prematurity and has atrophy of the left hemisphere.

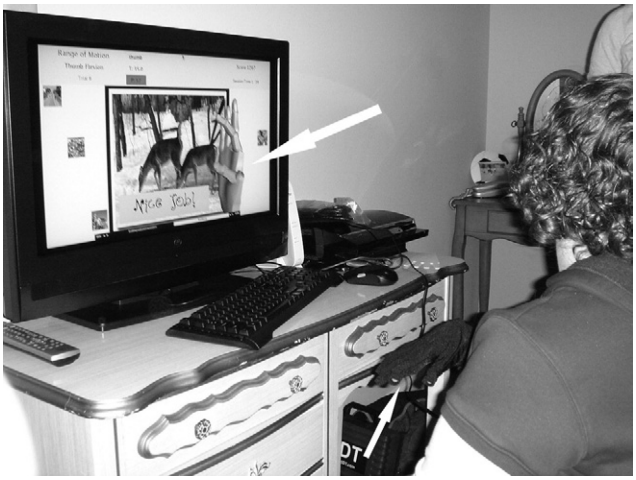

Fig 2. Subject 2 practices in her bedroom. Note the 5DT sensor glove on her plegic right hand (small arrow) and the avatar on the video screen (large arrow).

backup, and upgrading purposes. Access to the PlayStation3 was secured behind a firewall and password protected. The 5DT 5 Ultra Glove was originally designed for computer animation; it is constructed of elastic material and uses fiber optic sensors in each of the 5 fingers to sense changes in global finger position. Child-sized 5DT gloves were custom-built by the company for 2 subjects; the third has an adult-sized hand. The PlayStation3 was chosen because of its ability to run a Linux operating system,[c] which allowed the exercise games to be programmed using the open source Java3D API.[d]

All the games involved either finger flexion/extension or thumb movement, and were modeled on earlier games developed at Rutgers University for training adults with chronic stroke.[22,23] These earlier games used WorldToolKit software,[e] which is no longer commercially available, and a more expensive CyberGlove[f] sensing glove. Each subject followed instructions on the screen, with points awarded based on degree and speed of movement and level of difficulty. The subject calibrated the glove at the beginning of each session by opening and closing the plegic hand and moving the thumb. The games incorporated VR with an avatar of the child's hand on the screen during each game (see fig 2). Regardless of the subject's hand orientation, the avatar was always vertical. The subject's hand did not have to be in the same orientation. The glove used did not measure wrist orientation. However, subjects did not have a problem with this and, in fact, adapted easily to this mapping. Even if subjects could barely move their fingers, the avatar on the screen would make a complete movement, giving functionality in the game that they did not have in daily life. One game, "sliders," trained finger and thumb ROM as subjects opened and closed their hand or moved the thumb to make pictures appear. When games promoted finger ROM to "clean" the screen and reveal a hidden picture, each finger (forefinger to fifth finger) was responsible for "cleaning" one fourth of the screen. When the thumb was trained, its movement "cleaned" the whole screen. The second game, "chase away a butterfly," trained speed of movement by asking the subject to chase a butterfly. Butterflies were chased by flexing or extending the plegic fingers fast enough, before the butterfly flying from the side of the screen reached the hand avatar. Subjects were asked to practice at least 30 minutes a day, 5 days a week. Data from each session were uploaded to a clinical database server at Rutgers University.

Subjects were initially exposed to the games at a several hour-long introductory session 2 months before the study began. When the systems were installed in the homes, each subject tested the system while members of the research team were present. A team-written "user's manual" and ongoing technical support were provided by the team, but all 3 subjects understood how to use the system by the end of "installation day."

Baseline Assessments and Outcome Measures

Baseline and follow-up occupational therapy, forearm bone health, and fMRI assessments were performed. The baseline assessment was performed up to 1 week before the videogame exercises began. The systems had been installed in the subjects' homes for 84 to 90 days at the time of follow-up assessments. The systems were inoperable for 1 week in the middle of that time because of technical difficulties: malfunctioning televisions, faulty Internet connections, and software glitches that were subsequently fixed.

Occupational Therapy

Hand grip and pincer grip strength were measured using a Sammons Preston Jamar dynamometer and pinchometer,[g] respectively. The same instruments were used on all 3 participants at baseline and follow-up. The subject was seated in a chair with hips and knees both at 90° of flexion. The upper extremity tested was positioned with the shoulder at neutral and the elbow at 90°. The average of 3 measurements was taken for each test. Hand function was assessed using the Bruininks-Oseretsky Test of Motor Proficiency[24] and the Jebsen Hand Function Test.[25] The Bruininks-Oseretsky test included tests of fine motor precision, fine motor integration, manual dexterity, upper limb coordination, and bilateral coordination. The Jebsen test included 7 tests of hand function meant to reflect real-life use, such as lifting small or large objects (table 1).

Remote Measurement of Finger Range of Motion

The 5DT sensor glove measures finger ROM using raw sensor values from 0 to 4096; these were recorded during daily baseline measurements, stored remotely, and graphed. Subsequent linearity analysis[26] determined the mapping between 5DT glove readings and finger global bending angle. It was possible to indirectly determine the improvement in the "global" (non–joint-specific) ROM in degrees.

Forearm Bone Health

Forearm bone health was assessed using DXA and pQCT. Both forearms were assessed to enable within-subject normalization of artifacts (ie, changes due to growth and nutrition). DXA was used to assess area bone mineral density (g/cm^2), BMC (g), and projected bone area (cm^2) of the total distal radius by using a Hologic Discovery-W machine equipped with APEX 2.0 Software.[h] pQCT using an XCT-2000 machine[i] was used to take a single 2-mm-thick tomographic slice of the ultradistal radius at a distance of 4% of total bone length proximal to its distal end. pQCT scans were performed using a 0.4-mm voxel size, and analyzed using contour mode 1 (threshold = 169mg/cm^3) to derive total volumetric bone mineral density (mg/cm^3), BMC (mg/mm), and projected bone area (mm^2). Based on duplicate measures taken in 12 healthy per-

Table 1: Occupational Therapy Assessments: Improvements in Right Plegic Hand

	Subject 1		Subject 2		Subject 3	
Variables	Before	After	Before	After	Before	After
Grip (lb)	4*	5	10[†]	12	18.6[†]	23.6
Lateral pinch (lb)	0	Trace[‡]	0	Trace[‡]	3.8	2.1
Tip-to-tip pinch (lb)	0	0	0	Trace[‡]	0	0
3-point pinch (lb)	0	0	0	0.5	0	0
Jebsen						
Writing (s)	Unable	Unable	182[§]	118	43	87
Simulated page turning (s)	70	45	25	26	39	26
Lifting small, common objects (s)	101	71	134	34	120	33
Simulated feeding (s)	77	158	162	100	56	75
Stacking checkers (s)	Unable	46	26	28	Unable	84
Lifting large, light objects (s)	85	51	12	9	Unable to lift	27
Lifting large, heavy objects (s)	Unable to lift	49	16	10	Unable to lift	82

NOTE. Shaded areas highlight tasks where the subjects improved after 3 months of videogame telerehabilitation.
*Norm for age, 36–69lb.
[†] Norm for age, 42–67lb.
[‡] Trace movement of needle on gauge.
[§] Maximum time for this test is 3min (180s); subject was unable to complete task within allotted time limit.

sons, our laboratory can detect with 95% confidence an LSC between 2 successive assessments of .04g and .85mg/mm for BMC assessed using DXA and pQCT, respectively. The LSC is the minimum change that constitutes a real change above that of the measurement error (ie, precision), and is calculated at the 95% confidence level by multiplying the precision (expressed as the root-mean-square SD) by 2.77.[27]

Neuroimaging

All structural and fMRI scans were acquired during the same session on a Siemens MAGNETOM TIM Trio 3T whole-body scanner.[j] A gradient-echo, echo-planar sequence was used to provide whole-brain coverage for fMRI (TR=2250ms, TE=29ms, FOV=220mm, NEX=1, FA=79°, matrix=88×88, 39 axial slices, 3.5-mm slice thickness, no skip [voxel dimensions, 2.5×2.5×3.5mm]). Initial volumes before spin saturation were discarded. T1-weighted MP-RAGE scans were acquired for coregistration and display purposes (TR=2300ms, TE=2.91ms, FOV=256mm, NEX=1, FA=79°, matrix=256×256,160 sagittal slices, 1.2-mm slice thickness, no skip, in-plane resolution 1.0×1.0mm). Representative images demonstrating each participant's infarction territory are demonstrated in figure 1. The block-design fMRI motor task used a set of 2-Hz paced tones for patient response, with pseudorandom left hand, right hand, and rest conditions. Patients were asked to clench and extend all fingers of the hand in synchrony with the paced tones. They were instructed to do the best they could with the plegic hand and to attempt as much as possible not to move the unaffected hand when moving the affected hand. Data were processed and analyzed using SPM5.[k] Preprocessing steps included slice timing correction, spatial realignment, coregistration of fMRI images to the MP-RAGE volume, and spatial smoothing to a full width half maximum of 6mm. Statistical contrasts compared movement of the affected hand with that of the unaffected hand (ie, brain activation during movement of the right hand greater than left hand). Activation maps are displayed at a statistical threshold (uncorrected) of P equal to .001, with a cluster extent threshold (k) of 75 voxels.

RESULTS

Practice Time

Subject 1 practiced 60 days, and was signed on to the telerehabilitation system an average of 20.5 minutes a day, for a total of 20.5 hours. Subject 2 practiced 67 days, and was signed on to the system for an average of 22.5 minutes a day, for a total of 25.13 hours. Subject 3 initially practiced regularly, then became frustrated with equipment technical problems and stopped practicing. When he acknowledged that he was not practicing, the system was examined and found to require repair. In total, he practiced 36 days, and was signed on to the system an average of 21.5 minutes a day, for a total of 12.9 hours.

Occupational Therapy Assessments

All 3 participants showed improvement on grip testing and the Jebsen test, including a clinically meaningful improved ability to lift light and heavy objects (see table 1). The occupational therapists reported that subjects 1 and 2, who practiced more consistently, made more qualitative improvements in hand use than subject 3, but our measurement tools could not quantify those types of improvement (J. Havey and B. Shirley, oral and written personal communications June–August, 2008). The Bruininks-Oseretsky test did not detect clinically significant changes in function.

Remotely Monitored Range of Motion

Finger ROM improved for 4 of 5 fingers in subject 1 and for 3 of 5 fingers in subjects 2 and 3, with improvements most notable in the thumb and forefinger (fig 3). Measurements were sometimes limited by glove dysfunction.

Forearm Bone Health

Participants had 39.4%±2.1% and 30.5%±0.8% less DXA-derived radial BMC and projected bone area in their plegic arm compared with their nonplegic arm at baseline (table 2). The 2 participants who practiced most regularly gained greater radial BMC in their plegic arm than nonplegic arm, as evident by BMC changes greater than the LSC for both DXA and pQCT. The participant who practiced the least had no change in radial BMC on either DXA or pQCT when compared with the LSC (see table 2).

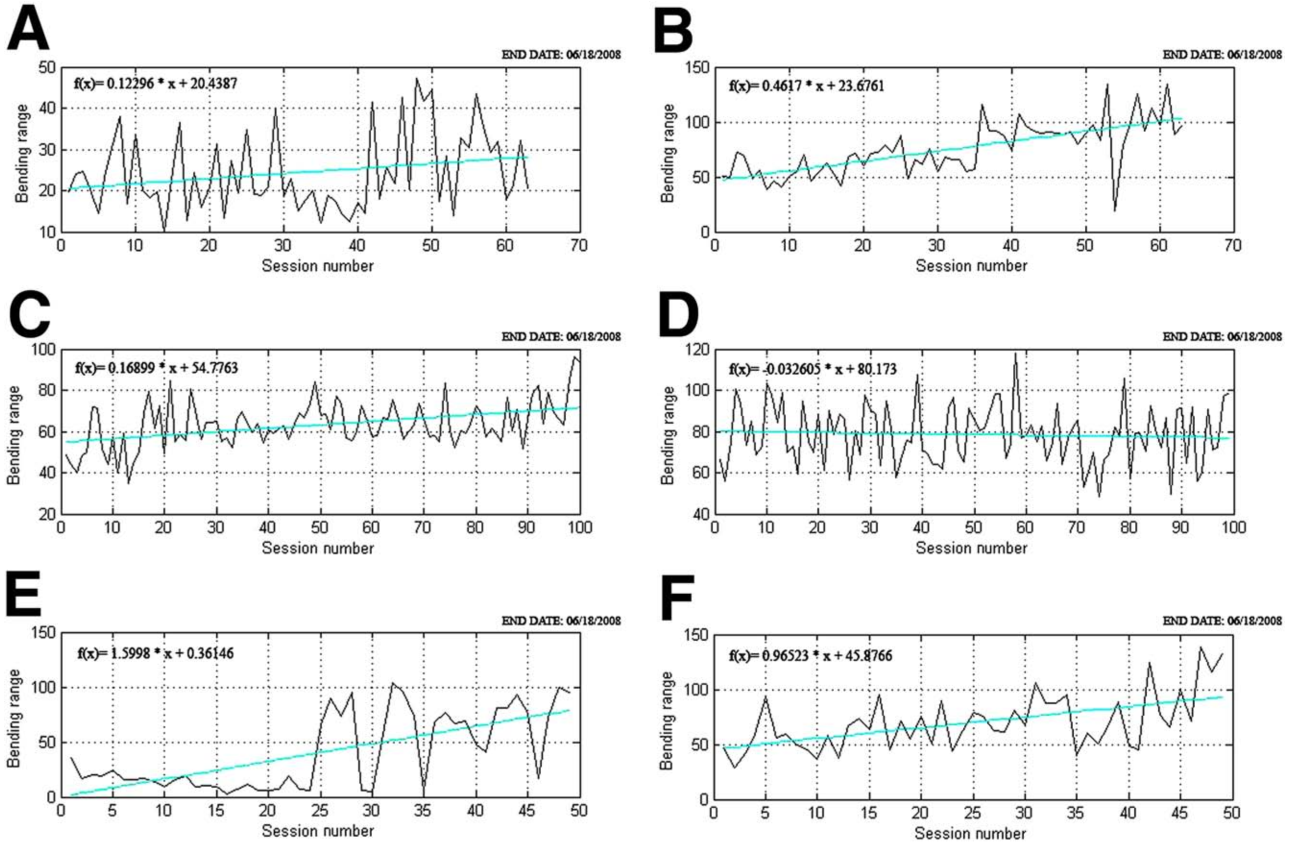

Fig 3. Increased ROM in the thumb and forefinger during the study. A session was defined as logging on, playing some games, and logging off. Subjects sometimes did more than one session a day if they signed off for snacks or phone breaks, or if they experienced technical problems. All 3 patients showed improved ROM in the thumb and forefinger except subject 2 in the forefinger; we suspect this was due to glove malfunction rather than lack of true improvement because she and her mother reported improvement in function, and the occupational therapists noticed improved quality of hand movement (which could not be quantitated on the measures we used). The *x* axis varies among subjects because they varied in how many sessions they did; improvement is graphed by session. (A) Subject 1: thumb bending over 3 months (B) Subject 1: forefinger bending over 3 months (C) Subject 2: thumb bending over 3 months (D) Subject 2: forefinger bending over 3 months (E) Subject 3: thumb bending over 3 months (F) Subject 3: forefinger bending over 3 months.

Functional Magnetic Resonance Imaging

At postintervention relative to baseline, all 3 participants showed expanded spatial extent of activation when moving the (impaired) right hand in brain regions important for motor function, including the primary motor cortex and cerebellum (see fig 4 for axial surface–rendered illustration of motor cortex activation changes and posterior views of cerebellum). Subject 1 showed one large cluster of contralateral (left) motor cortex

Table 2: Effect of Virtual Reality Videogame Telerehabilitation on DXA and pQCT Measures of the Distal Radius

	DXA Results							pQCT Results						
		Normal Arm		Plegic Arm		Change			Normal Arm		Plegic Arm		Change	
Subject	Outcome	Baseline	Final	Baseline	Final	Absolute*	Percent[†]	Outcome	Baseline	Final	Baseline	Final	Absolute*	Percent[†]
1	aBMD (g/cm^2)	1.15	1.20	1.00	1.02	−0.03	−3.0	vBMD (mg/cm^3)	355.1	336.8	378.3	367.8	7.80	2.1
	BMC (g)	4.74	4.72	2.82	2.88	0.08	2.8	BMC (mg/mm)	22.8	22.3	16.6	18.1	2.02	12.2
	B.Ar (cm^2)	12.48	12.16	8.61	8.69	0.40	4.6	B.Ar (mm^2)	64.3	66.2	43.8	49.1	3.38	7.7
2	aBMD (g/cm^2)	1.80	1.62	1.83	1.59	−0.06	−3.3	vBMD (mg/cm^3)	643.3	653.4	719.1	676.9	−52.30	−7.3
	BMC (g)	6.93	7.01	4.37	4.58	0.13	3.0	BMC (mg/mm)	58.3	59.5	42.9	45.1	0.97	2.3
	B.Ar (cm^2)	11.47	11.33	8.08	8.64	0.70	8.7	B.Ar (mm^2)	90.7	91.0	59.7	66.6	6.52	10.9
3	aBMD (g/cm^2)	1.86	1.61	1.87	1.66	0.04	2.1	vBMD (mg/cm^3)	658.0	638.4	453.8	415.7	−18.50	−4.1
	BMC (g)	10.17	10.19	6.03	5.98	−0.07	−1.2	BMC (mg/mm)	63.5	63.7	24.9	24.4	−0.76	−3.1
	B.Ar (cm^2)	16.49	16.44	11.41	11.03	−0.33	−2.9	B.Ar (mm^2)	96.5	99.8	54.9	58.7	0.50	0.9

Abbreviations: aBMD, areal bone mineral density; B.Ar, bone area; vBMD, volumetric bone density.
*Absolute change calculated as: (plegic final − plegic baseline) − (normal final− normal baseline).
[†] Percent change calculated as: (absolute change/plegic baseline)×100.

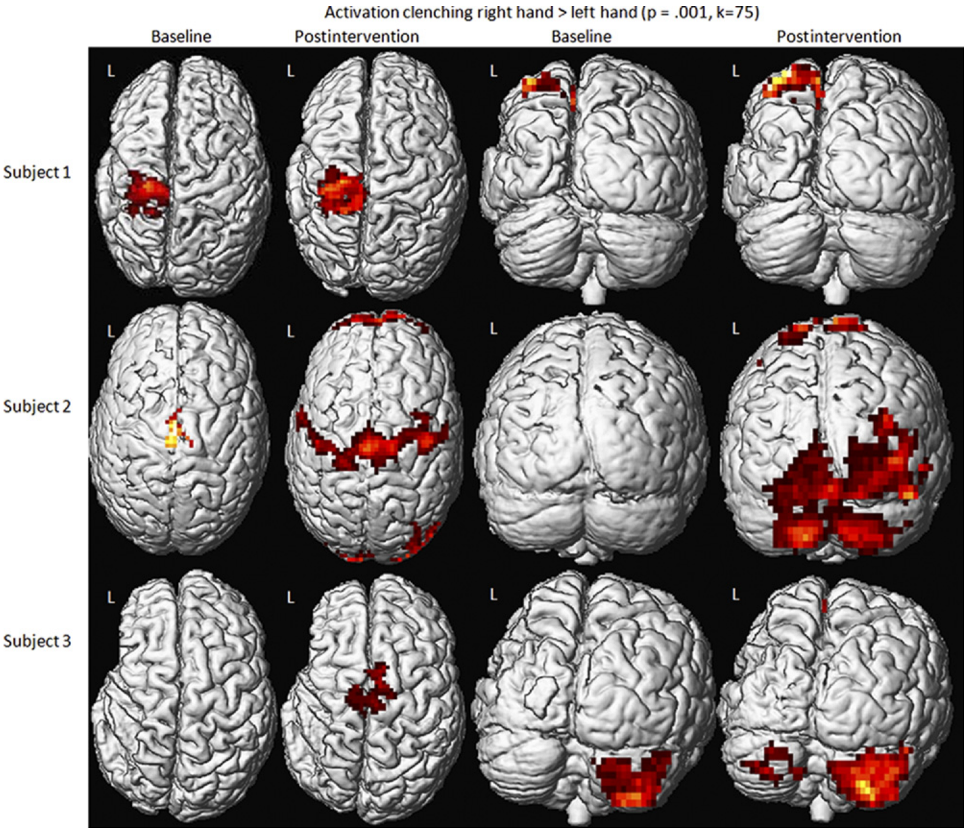

Fig 4. fMRI preintervention and postintervention, hand grip task. Note the increase in activation in all 3 subjects. Superior (first 2 columns) and posterior (second 2 columns) views are shown for all 3 subjects so that both cortical motor areas and cerebellum can be visualized.

activation at baseline, with more voxels activated at posttreatment, although he showed the least change of the 3 subjects. Subject 2 showed a small amount of midline motor cortex activation at baseline; at follow-up she demonstrated broad bilateral motor cortex and cerebellar activation, as well as activation of the frontopolar cortex. At baseline, subject 3 showed only ipsilateral (right) cerebellar activation, but at posttreatment, activation was observed in the medial motor cortex and cerebellum bilaterally. These changes were significant ($P<.001$).

DISCUSSION

This pilot proof-of-concept study suggests that videogame telerehabilitation can promote meaningful gains in hand function and forearm bone health as measured by DXA and pQCT in people with hemiplegic cerebral palsy who practice regularly. Our pilot study suggests that this therapy could benefit people who have "aged out" of early intervention programs, live far from rehabilitation centers, have comorbidities such as epilepsy that could preclude some other forms of therapy, and have extensive perinatal injury to traditional motor pathways (see fig 1). Improved function is accompanied by alterations in brain activation patterns during motor tasks on fMRI suggestive of increased engagement of brain regions important for motor skills, including the primary motor cortex and cerebellum. All 3 adolescents and their families expressed enthusiasm about the project.

Our work supports the findings of others who determined that VR videogames are a useful rehabilitative tool.[6-8,28-30] We have built on their work by adding in-home installation combined with remote monitoring. This increases the accessibility of rehabilitation for those who live far from rehabilitation centers and allows ongoing guidance from therapists and physicians who work far from their patients' homes. The system used in the current study has the potential to become relatively inexpensive for home use. In the future, rehabilitation games could be provided and monitored through the Internet; the primary hardware cost would be the glove.

Telerehabilitation—the provision of rehabilitation to distant patients through the Internet or phone lines—is an evolving field and offers the promise of cutting-edge care to patients who live far from clinical centers. A Minnesota pediatric telerehabilitation study[31] provided long-distance medical consultations to children in rural Minnesota and American Samoa; it was not used on a daily basis for in-home treatment. By contrast, there are multiple studies in adults that describe using telerehabilitation technology to provide in-home care.[32-37] We are not aware of any studies that provided in-home VR rehabilitative games for children. All 3 adolescents in our study lived in small Indiana towns at least 30 minutes from Riley Hospital, with limited local access to rehabilitation.

Osteopenia of the plegic limbs is an important issue for children with cerebral palsy[5] and adults with stroke or other causes of plegic limbs;[38] limb disuse is an important contributory factor. In children with moderate-severe cerebral palsy, osteopenia is common[39] and becomes worse over time.[40] Previous work has shown weight-bearing activity promotes improvements in bone health in children with cerebral palsy.[41] Although our study did not include weight-bearing exercises, the 2 adolescents who practiced regularly showed improvements in forearm bone health as measured by DXA and pQCT. It is unclear whether this was due to the game alone or to increased use of the hand and arm in general fostered by the improvements in hand function. This is an area for future study.

The baseline areas of activation on fMRI in our pilot study participants varied, perhaps in part related to the different etiologies of their cerebral palsy.[42] Consistently, however, we found increased spatial extent (ie, number of significantly activated voxels) of activation postintervention in motor-related regions, including the motor cortex and cerebellum. Other studies[43,44] have also noted increased areas of activation postrehabilitation. The increased range of finger motion may have contributed to the increased area of activation; this is an area for future study. MRI-compatible sensors exist for measuring hand movements during fMRI tasks,[45] and we may be able to incorporate them into future work.

Study Limitations

There are several limitations to this study. This was a small study, making it difficult to generalize the results. Multiple technical issues were encountered during the pilot study, due in part to the use of equipment not designed specifically for rehabilitation interventions that we adapted for this study. The sensor gloves were not designed for use on spastic hands with limited mobility; we are investigating ways to modify the glove or use alternative gloves for future work. Maintaining participant motivation was sometimes difficult because of these issues and because the study games were less engaging than commercially available games. Occupational therapists were not blinded to subjects' treatment status because this was a small pilot study in which all 3 subjects were treated. Our occupational therapy measurements did not fully capture subjects' improvements; for example, subject 2 only had small changes on the Jebsen, but her mother reported that she had started to use her plegic hand spontaneously to lift grocery bags and other household objects. In future work we will incorporate additional measurements to capture those changes. No formal measurement of task performance during fMRI was possible with the task paradigm used; in future work, we plan to use objectively monitored tasks to correlate changes in task performance with brain activation patterns. Video imaging was not part of the original assessment protocol; we will include this in future studies because of its ability to illustrate functional change (see *Archives* video presentation, *The Effect of Virtual Reality Videogame Telerehabilitation* [video] and detailed notes with timeline describing patient progress [appendix 1] available online at *http://www.archives-pmr.org*).

CONCLUSIONS

This pilot study suggests that in-home VR videogame telerehabilitation may improve hand function and forearm bone health in adolescents with hemiplegic cerebral palsy, and be accompanied by functional brain changes as demonstrated with fMRI. Further studies are needed to determine how much improvement is possible, whether this therapy can work better in conjunction with other new rehabilitative therapies, and whether adults with stroke and people with other forms of neurologic injury can also benefit. We believe this therapy could play an important role in the future of patient-centered neurorehabilitative care.

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SUPPLEMENTARY DATA

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.apmr.2009.08.153.

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Suppliers

a. 5DT 5 Ultra Glove; Fifth Dimension Technologies, 25 De Havilland Crescent, Persequor Park, 0020, South Africa.
b. PlayStation3 game console; Sony Corporation of America, 1 Sony Dr #3E6, Park Ridge, NJ 07656-8002.
c. Linux Online, 59 East River St, #2, Ogdensburg, NY 13669.
d. Java3D API; Java SE Desktop Technologies, Sun Microsystems, Inc, 4150 Network Circle, Santa Clara, CA 95054.
e. World Toolkit software; SENSE8 Product Line *http://www.sense8.com*.
f. CyberGlove Systems LLC, 2355 Paragon Dr. Suite D, San Jose, CA 95131.
g. Patterson Medical Supply Inc, DBA Sammons Preston, 1008 Cornerstone Dr, Mount Joy, PA 17552.
h. Hologic Inc, 35 Crosby Dr, Bedford, MA 01730.
i. Stratec Medizintechnik GmbH, Durlacher Str 35, D-75172 Pforzheim, Germany.
j. Siemens Medical Solutions USA, Inc, 51 Valley Stream Pkwy, Malvern, PA 19355.
k. Wellcome Trust Centre for Neuroimaging, Institute of Neurology, UCL, 12 Queen Sq, London WC1N 3BG, UK.

APPENDIX 1: SUPPLEMENTAL NOTES TO VIDEO: "THE EFFECT OF VIRTUAL REALITY VIDEOGAME TELEREHABILITATION"

Subject 1 progressed from being unable to open and close his plegic hand to being able to lift cans and stack them with that hand. "PS001" stands for "PlayStation subject 1"; our collaborators are involved in multiple studies.

The first video was shot in May 2007 when subject 1 came to get his hand measured for the glove. The video was filmed to help our collaborators at Rutgers University and the makers of the glove understand his motor limitations. At that time, he could not open his hand. In July 2007, he received botulinum toxin to the plegic wrist, but according to his mother, "he never really noticed any difference with his arm or hand." The videogame therapy began in mid-March 2008, almost 8 months after botulinum treatment; botulinum generally wears off after 3 to 4 months and does not last more than 6 months (Deborah Sokol, MD, PhD Riley botulinum clinic, oral personal communication). The second video was filmed by his mother in early August 2008 at our request, after slightly more than 4 months of practice. Both the subject and his mother agreed to let us use the video in lectures and publications because we kept his face hidden. His mother writes:

> I think the video game has helped greatly because he opens and closes his hand for 30 minutes straight. From my experiences with him in OT and PT over the years, the therapists did not have him open and close his hand for that amount of time in one sitting. They had other body parts for him to work on, and quite frankly, I don't think they had anything fun or interesting enough. I do think that the video game glove concept is great for focusing on and working on the hand.

Video imaging will be performed on all subjects in future studies.