The Potential of Virtual Reality and Gaming to Assist Successful Aging with Disability

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The probability for acquired disability increases with age.[1] Accordingly, the number of middle-aged and older adults living with disabilities will grow significantly as the United States population ages rapidly.[2] Emerging evidence from social and cognitive neuroscience suggests that new learning, productivity, and social engagement are possible for those aging with and into disability.[3] Although such evidence-based techniques and interventions are currently available, they are seldom used for those who are aging with and into disabilities. Moreover, research indicates that functional motor capacity can be improved, maintained, or recovered via consistent participation in motor exercises and rehabilitation regimens,[4] but independent adherence to such preventative and rehabilitative programming outside the clinic setting is low.[5] Given

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the importance and high costs of health care for those aging with disability, the applications of technology that can improve health maintenance and health care, or reduce the associated costs, would be especially valuable. Moreover, the technology needs to be introduced into everyday life well before sensory, sensorimotor, and cognitive impairments have occurred.[6] Such technology should not be centered only on disability and pathology, but should also be geared at promoting successful lifespan development at all ages.[7] It should be a pleasure to use,[8] and some would argue, a status symbol to possess.[9]

Maintaining functional independence is a high priority for those aging with and into disability. Advancements in computer technologies and information systems have the potential to assist in this goal by enhancing sensorimotor and cognitive functions required for day-to-day activities. As technology is rapidly being integrated into most aspects of life and is changing the nature of work, the form and scope of personal communication, education, and health care delivery has been transformed. It is highly likely that older people, specifically those aging with physical disability, will need to interact with some form of computer technology to carry out routine activities. Consequently, technology has the potential to enhance participation in community living and thus enhance the health and functional outcomes for individuals aging with disability because it may augment their ability and capacity to perform a variety of tasks that have traditionally presented a barrier to their daily living.[10,11]

One tangible way to show that virtual reality (VR) and gaming technologies can maximize function and participation for those aging with and into a disability is through the incorporation of outcome measures across the 3 disablement domains described in the framework defined by the International Classification of Functioning, Disability and Health (ICF) (**Fig. 1**).[12] The ICF classification system is an effective organizational framework to allow assessment of outcome interactions that are associated with health-related problems (ie, body function/structure impairments, activity limitations, participation restrictions) and across disease or injury-specific health conditions.[13] The true effect of a reduction in activity limitation on participation in home, work, and community life is of primary importance.

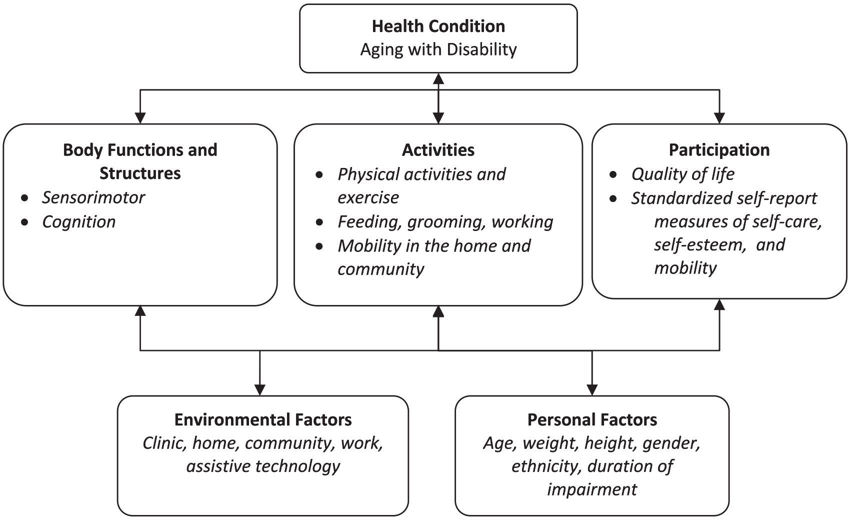

Fig. 1. ICF model as applied to aging with disability.

The application of VR and gaming technology that focuses on research and development of multimodal technology-therapy programs designed to address specific motor activity limitations (ie, posture and balance, dexterous manipulation, and integrated functional behaviors during wheeled mobility) presents an unique opportunity to address the challenges of linking multiple domains of the ICF, particularly in the context of negating the impairment at the body function/structure level (eg, game-based exercise for targeted and progressive strengthening), at the activity level (eg, Improved walking function because of game-based physical exercise), and at the home and community participation level (eg, increased family and social interaction when playing the games). For example, an individual who is recovering from a stroke may begin to play a home-based video game for hand and arm rehabilitation, but may benefit from the social interaction when playing with his or her grandchildren. The use of VR-based games can provide the means to address all the 3 disablement domains because a controllable range of stimuli can be delivered and systematically quantified at each stage of an intervention.[14]

This article presents an approach for maximizing function and participation for those aging with and into a disability by combining task-specific training with advances in VR and gaming technologies to enable positive behavioral modifications for independence in the home and community. This approach is unique, and stands in sharp contrast to the more conventional use of technologies that are primarily assistive, such as a device that can be used as a stand-alone assist for a specific task like walking (eg, a cane or walker). In this article, the authors present the rationale for the clinical application of VR and gaming technology, examples from the authors' work, and a description of some of the applications within their Rehabilitation Engineering Research Center on aging with disability (http://www.usc.edu/agingrerc). In each application, the authors combine the potential offered by immersive game-based VR technology with evidence-based rehabilitation approaches, such as muscle-specific exercises or sophisticated task-specific training protocols that harness the benefits of meaningful task practice for sustained improvements in sensorimotor functions, thereby fostering successful cognitive "unloading" and facilitating activity and social participation in home, work, and community life.

VIRTUAL REALITY AND GAMING TECHNOLOGY FOR SENSORIMOTOR AND COGNITIVE REHABILITATION

The effectiveness of sensorimotor function retraining is influenced by the quantity, duration, and intensity of practice.[15–21] High-intensity exercise programs are often fraught with low compliance and adherence. Exercise adherence is a significant hurdle to overcome, especially in the presence of a long-term chronic illness. Maintaining motivation and engagement are central to long-term functional improvement and success. Self-worth, motivation, and activity enjoyment have been reported to be vital to long-term exercise adherence.[22,23] It has also been suggested that when a client "focuses" on a game than his or her impairment, exercise becomes more enjoyable, motivating, and is more likely to be maintained over the many trials needed to induce plastic changes in the nervous system.[24–26] Providing a treatment that is fun, motivating, and distracting while simultaneously enhancing function would serve to improve exercise adherence and, therefore, effect motor learning and functional outcomes. One method that is showing great potential to meet this need is the use of VR games for rehabilitation.

VR is defined as "an immersive and interactive system that provides users with the illusion of entering a virtual world."[27] Immersion and interactivity suggest a virtual or imaginary world that can be entered and explored. Gobbetti and Scateni[28] 1998 state the "goal of virtual reality is to put the user in the loop of a real-time simulation, immersed in a world that can be both autonomous and responsive to its actions." The user is connected to the VR system as part of the input/output loop, allowing individuals to provide input to the virtual environment (VE) and experience the result of that input. In 2003 Burdea[29] described VR as "a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels." These definitions require that legitimate VR systems provide a computer simulated situation or environment with which the user can interact in real time, giving a sense of actually being in that situation or environment. To place the user within a loop of real-time simulation, VR systems require an output device or visual interface (flat screen or head mounted display) and input devices for interaction (mouse, joystick, data glove) and tracking (tracking device). The software or VE can be viewed through the output device and manipulated or interacted with via the input devices.[29] **Fig. 2** shows the components of a VR system.[29]

VR applications, historically used for the training of motor tasks involving highly complex activities such as surgical techniques,[30] flight simulation,[31] and military exercises[32] allow the user to enter a simulated world through multimodal sensory feedback. With the reduction in cost of computing hardware and software technologies,

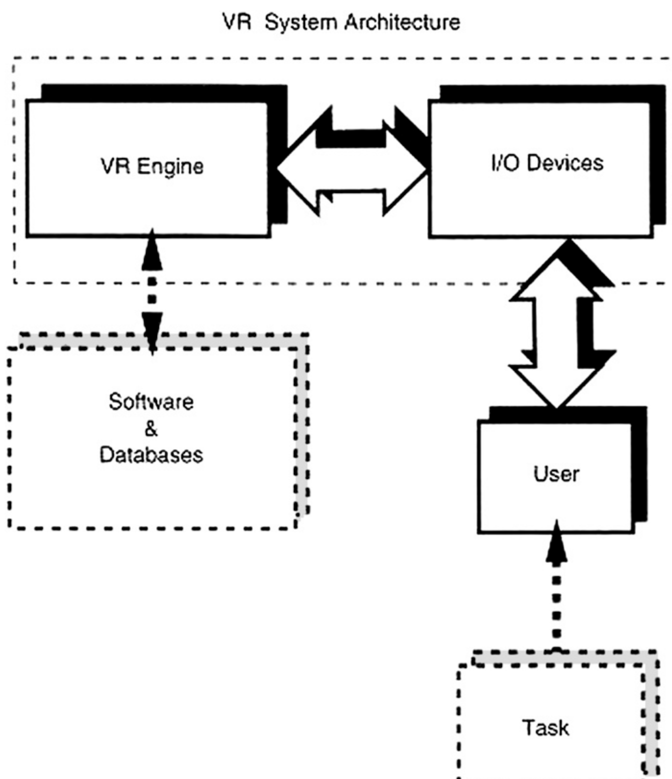

Fig. 2. Components of a VR system (I, input; O, output). (*From* Burdea G, Coiffet P. Virtual reality technology. 2nd edition. New York: Wiley; 1994, copyright 2003. Reprinted with permission of John Wiley & Sons, Inc.)

and the increasing expansion of the video game market, video game consoles and video games can be labeled as VR systems. These VR systems are interactive, immersive, and provide the user with a sense of presence within a VE. The use of video games and VR systems for rehabilitation has expanded rapidly over the past few years. Early research in the area of the use of VR systems to assist people to relearn how to move suggests that VR game-based technology can be used effectively to improve motor skill rehabilitation of a range of functional deficits. VR systems demand focus and attention, but can motivate the user to move, and can provide the user with a sense of achievement even if they cannot perform that task in the "real world."

There is a compelling and ethical motivation to address the needs of individuals who are aging with disabilities by promoting home-based access to low-cost, interactive VR systems designed to engage and motivate individuals to participate with game-driven physical activities and rehabilitation programming. The creation of such systems can serve to enhance, maintain, and rehabilitate the motor processes that underlie the integrated functional behaviors that are needed to maximize independence and quality of life beyond what exists with currently available, labor intensive, underutilized, and more costly approaches. There are fundamental and dramatic advantages inherent in the use of game-based approaches for treating cognitive, motor, and behavioral impairments. VR offers an ideal core technology because it allows for the creation of computer-generated 3-dimensional simulations, within which hierarchical task relevant challenges can be delivered and titrated across a range of difficulty levels.[33] In this way, an individual's treatment plan can be customized to begin at a stimulus challenge level that is attainable and comfortable for them, and then proceed with a gradual progression of challenge that is informed by the individual's performance in real time. Furthermore, VR game-based environments allow for the presentation of more ecologically relevant stimuli that are embedded in meaningful and familiar contexts. By designing VEs that not only "look like" the real world but also actually incorporate challenges that require real-world functional behaviors, the ecological validity of cognitive/motor interventions can be enhanced. Within such simulations, the complexity of stimulus challenges found in naturalistic settings can be delivered while still maintaining the experimental control required for rigorous scientific analysis and replication. Alternatively, it is possible that the use of novel environments and game play can engage and motivate the user to perform activities that they would not normally perform of their own accord. VR technology also supports precise and detailed capture and analysis of complex responses (ie, kinematic assessments of speed, accuracy, timing, consistency).

VR has recently been explored as a therapeutic tool to retrain faulty movement patterns resulting from neurologic dysfunction and to augment rehabilitation of the upper limb of patients in the chronic phase after stroke.[17,34] VR technology using specialized interface devices has been applied to improve motor skill rehabilitation of functional deficits including reaching,[35–37] hand function,[17,20,34,38–40] and walking.[41–43] Substantial effort and expertise have been focused on developing these innovative technology/interventions to exploit the neuroplastic properties associated with the sensorimotor systems in the adult brain. It has been proposed that such VR-based activities can be delivered in the home via a telerehabilitation approach to support these patients' increased access to rehabilitation and preventative exercise programming.[44,45] Moreover, when such VR training is embedded in an interactive game-based context, there is a potential to enhance the engagement and motivation needed to drive neuroplastic changes that underlie motor process maintenance and improvement. However, home-based VR systems need to be affordable, and easy to deploy and maintain, while still providing the interactional fidelity required to produce the meaningful motor activity required to foster rehabilitative aims and promote transfer to real-world activities.

Use of computer-based cognitive fitness and assessment technologies have rapidly expanded over the past 5 years with the introduction of a range of game-based training tools, such as BrainAge (Nintendo of America, Redmond, WA, USA), BrainFitness (PositScience Corporation, San Francisco, CA, USA), and Posit Science (Posit Science Corporation, San Francisco, CA, USA). Sales of cognitive fitness and assessment products in the United States have grown an estimated $100 million to $265 million between the period of 2005 and 2008.[46] Many products offer cognitive fitness games for regular long-term use. These brain-training games are often based on common neuropsychological assessment tools. Common areas of focus for games include long-term and short-term memory, language, executive function, visuospatial orientation, and critical thinking. The Posit Science program has been shown to reduce the effects of age-related cognitive decline through training in areas of memory, concentration, language, executive function, reaction time, and visual attention.[47,48] BrainFitness by Dakim (http://www.dakim.com/dakim) is a touch-screen device that assesses and trains long- and short-term memory, language, computation, visuospatial orientation, and critical thinking. These types of applications may include the neuropsychological tests that are often used for assessment, raising some concern that these tasks are training the user for the test rather than training the cognitive domain itself. Playing casual computer games has also been shown to improve cognitive abilities in older adults. Older adults who play video games have shown improvements in reaction time,[49–51] cognitive functioning,[52] intelligence,[53] visuomotor coordination,[53] attention and concentration,[54] and self-esteem and quality of life.[49,55] The use of physical computer games for improvement of cognitive and functional deficits has to be shown; however, several researchers across the globe are currently exploring the use of video game consoles, such as the Sony Playstation2 EyeToy (Sony Corporation, Minato, Tokyo, Japan) and the Nintendo Wii and WiiFit (Nintendo Co. Ltd, Kyoto, Japan) with groups of individuals who are healthy aged and those aging with a disability.

One of the issues with the use of commercial games and consoles such as the Nintendo Wii, Nintendo WiiFit, and Sony Playstation2 EyeToy is that these applications have been developed and tested for the purpose of entertainment. Commercial video game consoles and games have been tested on a diverse audience; however, they were not designed as medical devices or with a primary focus of a rehabilitation tool. Because these games were initially designed for entertainment, the game-play mechanics are not entirely applicable to those with disabilities. Thus, there is a need to gain a better understanding of the qualities of the commercial games and gaming consoles before these devices can be approved as appropriate rehabilitation tools for people with disabilities. Many of these applications are too difficult to use as a therapy tool by people with disabilities, and cannot be accessed or altered to improve usability.[56] The development of low-cost VR applications for rehabilitation must provide versatile and accurate interaction devices with the ability to track the user's movements and present information about performance to the user and their therapist in an appropriate and user-friendly format. The games and VEs must allow the user to interact in a way that is appropriate for their level of impairment, and must be easily changed to increase the level of challenge as the user improves.

The potential of the use of VR game-based applications, as they pertain to those aging with and into disability, involves the integration of cognitive and physical tasks within an engaging and meaningful environment in which it is safe to (or in some cases the system makes the user unable to) make mistakes and errors. The operating premise is that cognitive demand for daily functional behaviors increases with age-related physical decline. The approach is to enhance physical function in meaningful activities by harnessing advances in science and technology (especially immersive technologies) that increase sensorimotor capacity and unload cognitive demands in those aging with and into disability. By taking advantage of VR technologies for facilitating focused task-specific practice and gaming for enjoyment and adherence, it is anticipated that the core processes at the body function level and activities level as represented in the ICF model will be affected, which can enable active participation and enhance quality of life for the intended beneficiaries. Examples of clinical situations in which the use of VR and gaming technologies can serve to complement and improve on existing assessment and training applications are described in the following sections.

VR REHABILITATION FOR BALANCE IMPAIRMENTS

Balance, defined as the ability to maintain the body's center of gravity over the base of support, requires full integrity of an elegant and complicated system. Postural control is the ability to maintain an upright position (in sitting or standing) when stationary or when performing activities. The postural control system incorporates (1) sensory detection (through the visual, vestibular, and somatosensory systems), (2) integration of sensorimotor information within the central nervous system, and (3) proper coordinated movement patterns and responses.[57–59] When deterioration or damage occurs to one or more of these systems, impairment of balance occurs.[60–62] More specifically, an ability to accurately assess (sense) the position of the center of gravity relative to the base of support will disrupt balance. Second, when automatic movements to maintain balance are triggered too slowly or ineffectively, balance becomes distorted. Impairments affecting balance, such as muscular weakness, proprioceptive deficits, limitations in range of motion, and visual/vestibular deficits, can lead to falls and restrict an individual's normal motor activities, thereby limiting one's sense of independence, and adversely affecting the quality of life. The prevalence of balance disorders in the overall population of the United States is unknown. It is estimated that at least half of the overall population of the United States are affected by a balance or vestibular disorder sometime during their life (http://www.cdc.gov). Thus, there is a high probability that individuals aging with and into disability will experience balance problems sometime in their lifetime. Finding low-cost and safe balance training tools is imperative as the baby boomers continue to age and potentially increase the risk of falls.

The recent release and worldwide acceptance and enjoyment of Nintendo's WiiFit has provided significant evidence for the notion that exercise can be fun, provided it is presented in a manner that is entertaining, motivating, and distracting. The Nintendo WiiFit challenges balance in a variety of ways. By using a low-tech forceplate platform, the player controls the movements of an onscreen avatar by shifting their weight on the platform. When the player shifts right, the avatar shifts right and vice versa. Games such as hoola-hooping, defending a soccer goal, floating down a river, skiing down a mountain, and a variety of yoga positions are used in this device. This type of game challenges balance in a variety of ways. The player must watch, that is, engage the visual system, in a way that he or she can interpret the images presented and decide if movements to the right or to the left would be most successful. Visual feedback is given by, for example, seeing the avatar move between ski flags. Furthermore, knowledge of performance is provided visually as an individual moves into a yoga position, and is challenged to maintain his or her balance as precisely as possible by keeping a small red dot inside a yellow circle. Challenging the player to maintain the center of pressure and center of balance in a precise location while using visual feedback to guide the cursor on the screen tests the player's balance symmetry. The games challenge a person's vestibular system as the person moves through the challenging positions, and the vestibular system is being activated as the player moves into the various positions. If an individual has a deficit in any of these systems (visual, vestibular, or somatosensory) these games become a significant challenge. The Sony Playstation EyeToy has shown promising results as a low-cost tool for balance rehabilitation.[63,64] The EyeToy (Sony Computer Entertainment, Europe) is a projected video capture system that uses a motion-sensitive USB camera to display mirror image of the player into the game, allowing the player to interact with the VE using the entire body. In a feasibility study in 2007, Flynn and colleagues[63] applied the EyeToy with an individual with chronic stroke for 20 1-hour sessions. The game's task requirements included target-based motion, dynamic balance, and motor planning. The study showed clinically relevant improvements in the Dynamic Gait Index, and trends toward improvement on the Fugl-Meyer Assessment, Berg Balance Scale, UE Functional Index, Motor Activity Log, and Beck Depression Inventory.

Physical activities, including strengthening exercises, tai chi, dancing, and walking have been shown to improve balance and decrease the risk of falls in older adults.[65] Dancing is a fun filled, physical, and expressive activity open for participation by people of all levels of coordination. Modified dance-based exercises have been shown to improve endurance and balance in older adults.[66–68] Dancing can improve and maintain strength, endurance, balance, and coordination. Dancing can also increase body awareness and kinesthetic awareness, challenge attention, and improve self-esteem and confidence.[66–68] Dance-based training has been shown to be beneficial in improving static balance and reducing the risk of a fall.[67] The effectiveness of physical activity and aerobic exercise in preservation of balance and reduction of falls has been well documented.[65] A systematic review of prevention of falls exercise regimes found that the greatest relative effects of exercise on fall rates were seen in programs that included a combination of a higher total dose of exercise (>50 hours over the trial period) and consisted of challenging balance exercises (exercises conducted while standing in which people aimed to stand with their feet closer together or on one leg, minimize use of their hands to assist, and practice controlled movements of the center of mass).[65] Dancing can be considered a challenging balance exercise, because dancers are required to change their base of support while moving to music, not looking at their feet, and controlling their weight shift between poses or movements. Dancing can increase body awareness, kinesthetic awareness, and improve and maintain flexibility, balance, coordination, endurance, strength, and self-esteem.[69] Hopkins and colleagues[68] found in 1990 that a 12-week low-impact aerobic dance program significantly improved cardiorespiratory endurance, strength/endurance, body agility, flexibility, body fat, and balance in a sample of 53 women older than 65 years. Shigematsu and colleagues[67] in 2002 similarly found that, compared with a control group, a 12-week danced-based exercise class showed significantly greater improvements in balance measures (single leg balance, functional reach, and walking time around obstacles) in 38 women aged 72 to 87 years. Hui and colleagues[66] in 2009 found that a 12-week danced-based exercise program of a sample of 111 older adults significantly improved balance measures (6-minute walk test, flexibility, timed up-and-go test), resting heart rate, endurance, and physical and mental well-being (SF-36) compared with a control group. Most of the dance group felt the intervention improved their health status. These findings show that dancing has physical and psychological benefits, and should be promoted as a form of leisure activity for older adults. Dance games, such as Dance-Dance Revolution, first developed by Konami in 1998, are physically active video games that challenge endurance and dynamic balance. However, the primary function of current dance and music-based video games such as Dance-Dance Revolution is entertainment. These games are beneficial from a rehabilitative perspective because they require skills related to timing, rhythm, balance, endurance, and strength. Using a dance mat with areas that the player must step on in time with cues on the screen, these games have the ability to get the player to perform specific moves in a specific pattern, and have been shown to improve activity and mood as well as reduce weight in children and youth.[70–72] Dance-Dance Revolution has been shown to increase heart rate and motivate adolescents to exercise in an effort to improve motor coordination, self-esteem, and aerobic fitness.[70,72] Dance games are currently being used in schools and a variety of workplaces across the United States to encourage children and adults to become more active. These games have the potential to be used as a part of a balance training prevention program for older adults (with and without disability) in clinics or within the home.

VR REHABILITATION FOR A HOME EXERCISE PROGRAM FOR THE SHOULDER

An estimated 1.5 million people in the United States use a manual wheelchair.[73] The proportion of the population using wheelchairs increases sharply with age. In the population of age 18 to 64 years, 560,000 individuals use a manual wheelchair. This number increases to 864,000 in those 65 years and older. Four-fifths (80.2%) of wheelchair users in all age groups report some degree of difficulty in at least one activity of daily living. Of those aged 64 years and younger, spinal cord injury (SCI) is the most common diagnosis in manual wheelchair users.[73] Approximately 12,000 new survivors of SCI are added each year to the total population of approximately 300,000 persons now living with SCI (http://www.spinalcord.uab.edu, 2008). Improved life expectancy and increasing age at injury have resulted in a population that is increasingly experiencing the impact of aging with a disability.[74] One of the most common secondary complaints in the SCI population is shoulder joint pain that has been attributed to the high demand on the upper limbs during manual wheelchair use, transfers, and raises.[75–78] The incidence of shoulder joint pain after SCI is greater than that in the nondisabled population at every age and increases steadily with time post injury, affecting a full 70% of individuals at 20 years post SCI.[79] A consequence of the current near-normal life expectancy for individuals with SCI is that most of this population will eventually experience significant and function-limiting shoulder pain. Because individuals who use a manual wheelchair are dependent on their upper extremities for mobility and daily activities, shoulder dysfunction and pain can present a devastating loss of independence and decreased quality of life.[80] Although this clinical problem has been documented extensively in the SCI population, individuals with other primary diagnoses that preclude function of the lower extremities (eg, lower extremity amputation, poliomyelitis, myelomeningocele, multiple sclerosis) experience a similar course of shoulder pain with prolonged wheelchair use.[77,81–84]

Rotator cuff strengthening and shoulder joint stretching exercise programs modified for performance from a manual wheelchair have been shown to reduce shoulder pain and improve function in individuals who are dependent on manual wheelchair use for community mobility.[85–87] A randomized control trial confirmed the effectiveness of a home-based, progressive resistive exercise program that was designed to be simple and to require minimal equipment.[84] Participants in this trial had chronic shoulder pain (mean duration of 5 years) from prolonged wheelchair use after SCI (average time since injury 20 years). Shoulder pain, as measured by the Wheelchair User's Shoulder Pain Index (WUSPI),[67] was reduced after the 12-week exercise program in the experimental group from 51 to 15 out of a total possible score of 150. In contrast, WUSPI scores in the attention-control group were unchanged at a score of 45 after 12 weeks.[84] Moreover, participants in the experimental group showed a small but statistically significant improvement overall; subjective quality of life increased from 4.8 to 5.3 out of a total possible score of 7.0 where as quality of life scores were unchanged at 5.0 in the control participants. Thus this simple, low-cost home exercise program is dramatically effective at reducing long-standing, debilitating shoulder pain in individuals who use a manual wheelchair for community mobility.

A vital component to long-term adherence to an exercise program is maintaining the person's interest in the repetitive tasks and ensuring that they complete the training program. A lack of interest or short attention span can also impair the potential effectiveness of the exercise program. The use of rewarding activities and biofeedback has been shown to improve task performance and motivations to practice.[88,89] For instance, an interface (GAME[Wheels]) between a portable roller system and a computer that enables a wheelchair user to play commercially available computer video games during wheelchair propulsion exercise was shown to increase the individual's physiologic response, and allowed the users to reach their exercise training zone faster and maintain it for the entire exercise trial.[90–92] Moreover, of the 15 subjects tested, 87% indicated that having a video game during exercise would help them work out on a regular basis.[91] Similarly, a game-based arm exercise using an interface between an arm ergometer and a computer game (GAME[Cycle]) that allows the user to control game play on the screen as if using a joystick was shown to elicit the same physiologic response and perceived exertion as arm ergometry, but the games made the exercise more exciting and, thus, motivated a person to exercise more or for a longer period of time, yielding increased energy expenditure.[93] A shoulder strengthening and flexibility home exercise program performed to prevent the onset of shoulder pain would require long-term or intermittent commitment for individuals with chronic disability. Therefore, the development of a low-cost game-based application that can be deployed in the home environment is vital for long-term commitment to such a shoulder preservation program.

VR REHABILITATION FOR DEXTEROUS MANIPULATION WITH THE FINGERTIPS

Dexterous fingertip tasks are ubiquitous in daily life (eg, writing, sorting coins, or buttoning a shirt) and differ greatly from static pinch tasks (eg, holding a key or pressing a button) in that the magnitude and direction of fingertip forces need to be dynamically controlled to fulfill the task. The retention and restoration of hand function in aging, in injury, and in disease is the subject of an entire medical field.[94–97] Maintaining and restoring finger dexterity is a gateway to a productive and entertaining lifestyle for the elderly: from feeding and dressing oneself to using a cell phone or computer, to participating in a knitting club or playing cards. Dexterous manipulation with the fingertips is disproportionately impaired by orthopedic (eg, thumb osteoarthritis) and neurologic (eg, stroke, cerebral palsy, Parkinson disease, traumatic brain injury, and SCI) condition and natural aging because it requires a complex balance and interactions among all neuromusculoskeletal elements of the body: from cortical and spinal sensorimotor systems, to musculotendon integrity, to joint and ligament flexibility and stability of the hand.[98,99] The medical and rehabilitation communities are in dire need of effective means to promote the retention or restoration of dexterous manipulation in aging, and especially in aging with a disability.

To address this need, the authors have developed a novel engineering paradigm and technologies that focus on the ability of a person to perform dexterous fingertip tasks at submaximal force levels.[100] The manipulating ability of a multifinger hand is defined by the mechanical effect each fingertip can produce on an object.[101] Effective and dexterous manipulation arises when the coordinated action of the fingertips can generate the desired resultant 3-dimensional force/torque vector at the center of mass of the object being held. The ability with which the magnitude and direction of the fingertip force vectors are dynamically regulated determines the effectiveness of dynamic manipulation. The Strength-Dexterity (S-D) system targets the functional cornerstone of dexterous manipulation in healthy and clinical populations, which is the ability to simultaneously and dynamically regulate the magnitude and direction of fingertip force vectors. The S-D system is based on the principle of buckling of compression springs. When compressed the spring is initially stable, but as the compression increases to a critical point the combined handspring system becomes unstable and relies on the passive anatomic structures and active sensorimotor control of the fingers to dynamically hold that level of compression force. The compression of this device involves low forces (2–3 N), but requires careful collaborative control of finger motions and fingertip force vectors to prevent the spring from buckling. The one parameter that can characterize performance during the production of dexterous manipulation with the fingertips is the maximal compression a person can achieve with a spring that is impossible to compress fully. The maximal compression a person can achieve indicates the limit of sensorimotor integration ability by indicating how much instability the person can control. The S-D system has the potential to be used to quantify impairment and compare treatment outcomes in orthopedic and neurologic afflictions that degrade dynamic manipulation.[100]

The application of VR and a game-based system to rehabilitate hand and finger function in persons with stroke,[38,39,102] cervical level SCI,[103] and cerebral palsy[103] has shown promising outcomes. In 2004 Adamovich and colleagues[38] used a VR-based system for hand rehabilitation using a CyberGlove (Cyber Glove Systems, San Jose, CA, USA) and a Rutgers Master II-ND haptic glove that trained finger range of motion, finger flexion speed, independence of finger motion, and finger strength in 8 individuals with chronic stroke. All participants showed improvements in functional tests that transferred into gains in clinical tests and task completion times.[39] To rehabilitate finger-hand function in patients with SCI and stroke, Szturm and colleagues[103] in 2008 used an interactive computer gaming system, coupled with the manipulation of common objects, as a form of repetitive, task-specific movement therapy for 15 1-hour therapy sessions, 3 sessions a week. Participants could select from 25 different commercial video games (rated "everyone"), each offering different precision levels, speed constraints, visuospatial demands, and either single- or dual-axis movements. The training levels were progressive and emulated the functional properties of objects used daily. This therapy resulted in positive effects on the recovery of finger motion and hand function.

VR REHABILITATION AND STIMULATED ACTIVE SEATING FOR PRESSURE ULCER PREVENTION

Pressure ulcers (PUs) are a significant and frequent problem for those who depend on a wheelchair for mobility. Pressure ulcers are a debilitating pathology resulting from pressure and shear in the soft tissues of immobilized individuals who do not shift their weight.[104] Blood vessels become occluded and the soft tissues they supply become necrotic. PUs are particularly high in incidence in individuals who are insensate but who sit for long periods of time. About 30% of immobile people develop pressure ulcers at some time during their lives.[105] Age- and pathology-matched patient trials have shown that hospital stays increase 3- to 5-fold in patients suffering from PUs, incurring significant hospital expense.[106] Pressure, immobility, and disuse atrophy also contribute to a high incidence of PUs in elderly patients who lose mobility from stroke, dementia, Parkinson disease, and so forth. The cost of treating PUs in the United States was estimated to be more than $55 billion annually in 1994 (average increase in hospital stay of 21.6 days at $2360 per day in almost 1.1 million patients per year).[106] Current treatment of PUs requires prolonged passive tissue load reduction, when individuals are required to be removed from their seating systems, sometimes in bed for long periods of time. In some cases, surgical repair is required. Even when healed, PUs have a high (more than 60%) recurrence rate,[107] with the monetary costs for treatment ranging from $50,000 to $80,000 per incident. A pressure ulcer is devastating on personal well-being, self-esteem, and the ability to contribute to and participate in society in general.[108] Thus, prevention of occurrence or recurrence of PUs are a high priority for aging wheelchair users.

Today's strategies require cognitive awareness to manually or mechanically shift weight several times each hour. When individuals are actively engaged in activities of daily life, this cognitive burden is often lost and can result in pressure breakdown of high-risk sitting areas, such as the ischia, sacrum, and sometimes over the trochanters.[109–111] Stimulated active seating for pressure ulcer prevention (SASyPUP) is designed to allow significant weight relief, especially over the ischia, on a preprogrammed schedule. The SASyPUP uses chronically implanted, wireless microstimulators[112,113] to deliver preprogrammed stimulations to electrically activate the gluteal muscles to shift the paralyzed participant's weight, as well as to build up gluteal muscle volume (padding) and musculocutaneous circulation for exercise, and hamstring muscles as hip extensors. Implanted neuromuscular electrical stimulation has been shown to activate strong muscle contractions and to produce skeletal motion, with associated increases in muscle bulk (hypertrophy), strength, and metabolic capacity, as well as vascularization.[112–115] Thus the stimulation has the potential to counteract the 3 major etiologic factors in PU development: immobility, soft-tissue atrophy, and hypoxia. The individual does not need to generate cognitive strategies for weight shifting, because implanted microstimulators will automatically activate muscles to shift pressure. This will serve the seated individual who lacks sensation much more like the automatic position changes used by seated individuals with intact sensation.

Unlike individuals with normal sensation, who subconsciously automatically shift their seated weight, the SASyPUP system shifts the user, but without the coordinated trunk muscles used to maintain upright balance. Thus there is the potential to shift the seated individual and alter their base of support unexpectedly. In this instance, a unique application of VR and gaming technology helps in enhancing sitting posture and balance to allow individuals to practice and develop automatic strategies to maintain upright seated balance both at rest and while experiencing the periodic stimulated weight shift. Conceptually, the stimulated cycles can use a gradual ramping up of the weight-shifting contraction, and users of the system will be made aware of the impending weight shift so that appropriate and perhaps automatic compensations can be employed. Because the SASyPUP system is engaged during most of the day while participants are in their wheelchair, a wide range of activities and postures may be interrupted by the weight-shifting stimulation. The VR and gaming applications can allow users to develop and practice strategies that will minimize the potential loss of balance regardless of position or activity in which they are engaged when the weight-shifting cycle begins.

SUMMARY

The use of VR technology to design games with a focus on augmenting traditional rehabilitation interventions will likely play a large part in the future of treatment and training of people aging with and into a disability. More research is required in several areas before this technology can be incorporated into daily life and rehabilitation plans, including a systematic analysis of the characteristics of optimal design and use of VR games in the clinic and home environment, increasing the capacity to conduct interdisciplinary research and knowledge translation in the emerging area of VR and gaming applications for those aging with or into disability, and the effective incorporation of VR and games technology into the clinical setting and proper potential incorporation (through commercialization) of low-cost VR technology in the home environment. In addition to translational research, Adamovich and colleagues[116] suggest a need for future research to follow several important paths. There is a need for imaging studies to evaluate the effects of sensory manipulation on brain activation patterns and the effects of various training parameters on long-term changes in brain function. Larger clinical studies are also needed to establish the efficacy of sensorimotor rehabilitation using VR in various clinical populations and, most importantly, to identify VR training parameters that are associated with optimal transfer to real-world functional improvements. Finally, the application of robust outcome measures across the 3 domains of functioning as defined in the ICF, particularly in the participation domain, is vital for the development of evidence-based guidelines regarding the effectiveness of VR and gaming interventions that could have the potential to impact the local and national agenda for the future.

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