

Technology-assisted and motivational programme for a blended approach to prevent and manage balance, gaze, mobility and cognitive decline with age

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Abstract

Introduction

Mobility limitations and cognitive impairments which are common with ageing, cause a reduction in the levels of physical and mental activity and are prognostic of future adverse health events, including falls. Consequently, multi-task training paradigms that simultaneously address both mobility and cognition benefit healthy ageing and are important to consider in rehabilitation. In this regard, the application of computer technology provides a number of promising approaches, in particular, virtual reality and therapeutic gaming. These approaches have the potential to improve clinical outcomes by making therapy more motivating, more ecological, and effective, blending of balance, mobility, gaze and cognitive exercises/tasks. Using a computer-based platform, one can also objectively quantify duration and intensity of both exercise and cognitive activity. Performance can also be quantified, trend analysis can be conducted and dose-response relationships established. The aim of this critical review is to discuss the technology-assisted and motivational programme approach to prevent

and manage balance, gaze, mobility and cognitive decline with age.

Conclusion

There is a need to develop and validate low-cost, engaging exercise and cognitive platforms with automated monitoring tools that can extend quality health care and support to the community and ultimately the home.

Introduction

Successful ageing has become one of the most important aspects of health care in the 21st century. As people live longer, they are at higher risk for developing cumulative illness and chronic disability, and are vulnerable to the negative effects of increasingly sedentary lifestyles. For example, mobility limitations and cognitive impairments, which are common with ageing and often coexist, cause a reduction in the levels of physical and mental activity and are prognostic of future adverse health events, including falls and depression^{1,2}.

It is well established that physical activity will improve cardiovascular outcomes and reduce risk factors for heart and stroke disease³. It has also long been recognized that an increase in level of physical activity does translate to improved muscle endurance and balance^{4,5}. Findings from a growing number of clinical trials with older adults provide strong evidence that regular physical activity or moderate aerobic exercise will prevent the progression and development of vascular cognitive impairment and Alzheimer's dementia⁶⁻⁸. In this regard, cardiovascular health and fitness through exercise has been shown to improve

cerebral blood flow, promote the maintenance of grey matter brain volume and thereby slow the rate of cognitive decline^{6,9}. A number of cognitive training programmes have also been developed aimed to improve specific executive cognitive functions, abilities that commonly show impairment with age^{10,11}. These processes underlie a variety of daily tasks, for example, safe, independent community walking (outdoor and public) requires a high level of mobility skills, as well as cognitive flexibility to address threats to balance while attending to a range of environmental demands, unpredictable conditions and concurrent cognitive tasks. In the past, mobility and cognition were seen as separate processes and have not been studied together. More recently, these systems have been shown to interact together in our daily functioning. Consequently, dual-task (DT) training paradigms simultaneously address both mobility and cognition during function, and many believe would benefit prevention and rehabilitation¹². This paper discusses DT programmes and the effect they have on preventing and managing balance, gaze, mobility and cognitive decline with age.

Discussion

The authors have referenced some of their own studies in this review. These referenced studies have been conducted in accordance with the Declaration of Helsinki (1964), and the protocols of these studies have been approved by the relevant ethics committees related to the institution in which they were performed. All human subjects, in these referenced

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studies, gave informed consent to participate in these studies.

Balance impairments and mobility limitations can occur due to singular events or can have an insidious onset, with the problem source found in multiple predisposing factors, such as gradual decline with age of cardio-respiratory fitness, musculoskeletal fitness or neural fitness (sensory cognitive motor). Each of these systems that underlie mobility has a certain amount of capacity or functional reserve. Walking problems, in particular outdoors, become evident when this functional reserve drops below a threshold level and compensatory strategies have failed. In addition, many of the common neurological diseases that affect older adults, such as, visual impairment, stroke and dementia significantly compromise balance and mobility. For many older adults, even small disturbances will result in a fall, with a high likelihood of injury. It is important to note that for older adults, community ambulation is strongly associated with the preservation of skills for independent living, community participation and healthy ageing.

A growing body of evidence reports that abilities that commonly show impairment with age are those associated with performing DTs in which goal-directed behaviours have to be flexibly maintained, monitored and implemented in face of changing memory loads, processing speed, distractions and unpredictable conditions. The DT paradigm is a procedure that requires an individual to perform two simultaneous tasks, for example, walking while performing a cognitive task¹³. This allows grading of performance of each task individually, and most critically, evaluation of potential interactions in the influence that information load has on walking behaviour. A better understanding of the interactions between physical demands, cognitive load and type of task will be important for identifying high-risk scenarios that people will

encounter in their daily life activities. Studies have put forth the affirmation that difficulty in the ability to assign attention and processing resources to each task simultaneously contributes to increased fall risks¹⁴. Poor DT performance in either the motor or cognitive task could also be caused by altered prioritization between the two tasks¹⁵. The most common and consistent finding of DT studies comparing walking alone to walking plus performing a cognitive task has been the reduction of gait speed¹³. This likely account for a change in strategy is in preparation for concurrent processing of two tasks. Reduced gait speed is commonly observed in many older adults, and a slowing of gait speed is also observed when negotiating obstacles and irregular or unpredictable terrains, i.e. threats to balance¹⁶.

Critical appraisal of the validity of relevant articles

Most commonly DT assessment paradigms have utilized general cognitive tasks, like walking while talking, verbal fluency or number subtraction that are typically only assessed qualitatively, do not involve the visual-motor system and are limited in what individual brain areas are recruited¹³. Visual processing of spatial orientation cues, object locations/motions and their spatial relations with respect to body and space, as well as for navigation are important aspects of balance and locomotor skills. There are a number of key pieces of evidence that support the view that visual-spatial processing is an important aspect of cognition to explore as a factor involved in both mobility decline and fall risk^{17,18}.

A number of recent studies have used computer-based proxies or games to probe and evaluate visual spatial perception, processing speed and cognitive interference^{19,20}. One such test, Useful Field of View (UFOV) is a validated, computer-based test that requires visual search

mechanisms and the ability to select relevant information and ignore irrelevant information (cognitive inhibition)²¹. Studies have found that older adults with slower cognitive speed of processing, as measured by the UFOV test, experienced the greatest mobility loss²². In a similar manner, a number of studies have used reaching or pointing tasks to evaluate perception and higher-level cognitive decision-making^{23,24}.

It has been suggested that effective programmes to prevent falls in older adults should focus on training mobility and cognitive functions together^{10,12}. In this regard, the application of computer technology provides a number of promising approaches, e.g. Anderson-Hanley (2012)¹⁰ showed that coupling recumbent cycling exercise with a virtual reality task (using a hand held gamepad to move an avatar in a virtual outdoor environment) did enhance executive function and clinical status more than aerobic exercise alone. Another promising approach involves virtual environments, viewed during treadmill walking, which provides a more ecological and task-orientated approach to DT mobility training^{25,26}. A treadmill is an excellent choice to conduct core balance, walking stability and gait assessment within the DT paradigm, i.e. walking while viewing a standard LCD/LED monitor which can be used to present a broad, diverse array of cognitive content and therefore can incorporate many types and levels of executive functions²⁷.

Treadmills are widely used clinically, and have become a commonplace in most fitness, wellness and community centres. DT treadmill walking has important advantages versus DT over ground walking. A number of studies have demonstrated that spatial-temporal and kinematic gait variables (average values and variation) are significantly influenced by walking speed^{28,29}, and reduced gait speed is a highly consistent strategy

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used during DT over ground walking¹³. Therefore, speed is a confounding variable when interpreting effects of DT protocols on most gait variables. Treadmill walking is a convenient method to select and ensure a steady state average walking speed among subjects and over time. Treadmill walking also provides an uninterrupted gait where hundreds of consecutive steps can be obtained in a few minutes. Even though data collected from 5 to 20 strides (i.e. in gait laboratories or during repeated walks over short, instrumented walkways, such as Gait Rite[®] may reliably measure gait speed, this is not sufficient for measures of gait variability or periodicity measures, in particular, during DT walking or for older adults with mobility limitations^{30,31}. Moreover, in most over ground DT studies the walking task and the concurrent cognitive task is only performed for a few metres. This results in recording verbal responses from only a few consecutive events and for a few seconds. Another important issue when treating and testing people with balance and mobility limitations is safety. A treadmill with variable speed and handrails is an effective means to prevent any untoward event during training.

Proof-of-concept of a computer-based therapeutic gaming platform (TGP), which integrates a number of game-based exercises and cognitive activities has been provided by Szturm and colleagues^{4,27,32,33}. The TGP was designed for targeted exercises and activities that can incorporate:

- (a) Core balance skills.
- (b) Locomotor skills.
- (c) Gaze control and visual tracking.
- (d) Executive cognitive functions (processing speed, working memory, cognitive inhibition).
- (e) Dual-tasking, combinations of above.

The TGP integrates treatment and assessment and the approach is based on the following principles.

1. Modern concepts of learning and neuro-adaptation are incorporated using a task-specific approach^{34,35}. Participation in meaningful physical and mental activities is required to:

- (a) Maintain skills and neural-muscular fitness,
- (b) Drive neuro-adaptation (plasticity) sufficient for recovery from injury,
- (c) Limit negative plastic changes that occur when people begin to reduce activity levels and simplify behaviours that become difficult to perform.

It is hypothesized that DT training targeting core balance and treadmill walking exercises coupled with cognitive activities using interactive, 'therapeutic' computer games will improve walking capacity and executive cognitive function. Physical exercises will have some overflow effect on cognitive skills and vice versa, and combining them together would have a more substantial effect.

2. Maximizing participation is also seen as a main goal of intervention. Long-term exercise/training programmes are often fraught with low compliance and adherence, especially in the presence of a chronic illness, or growing decline in physical and mental capacity. Maintaining motivation and engagement are thus central to long-term functional success. An emerging methodology is to couple exercise and activities to 'therapeutic' computer games, thus making exercise training both a challenging and enjoyable experience. Video games have been shown to be an effective means of enhancing visual attention, processing speed and global cognition in older adults. Research has shown that training on complex video games that stress rapid responding to fast-paced display changes, transfers to a wide variety of perceptual and attention

skills such as useful field of view, multiple-object tracking and enhanced visual short-term memory skills^{10,19,22}.

Components that make up the TGP

- Standard treadmill fitted with a treadmill pressure sensor mat. (Vista Medical Ltd., Winnipeg, Canada)³⁶. The pressure mat consists of an array of piezo-resistive sensors secured to the treadmill bed beneath the moving treadmill belt. This provides unobtrusive recordings of calibrated foot-ground forces from hundreds of sensors. See Figure 1 for illustration of the platform and typical recording. Methods have been derived²⁷ to quantify the following variables during treadmill walking from hundreds of consecutive steps;

- (a) Quantification of various features of the segmented movement trajectories (i.e., players' contextual actions) for each cognitive game provide a basis for objective quantification of cognitive functions, which include (i) game success rate (percentage of target caught), (ii) average motor response time (time from appearance of the target to start of the paddle movement), (iii) average movement execution time and (iv) movement efficiency.
- (b) Spatial-temporal gait parameters, e.g. stance/swing times, step width, in a manner identical to over ground walking on the Gait Rite walkway (Figure 1).

Documenting safety is an important part of any balance mobility exercise programme for 'at risk' older adults to inform therapists and trainers when and how a client is performing, whether they are experiencing any difficulty, and how they are progressing in their individualized exercise programme. Although

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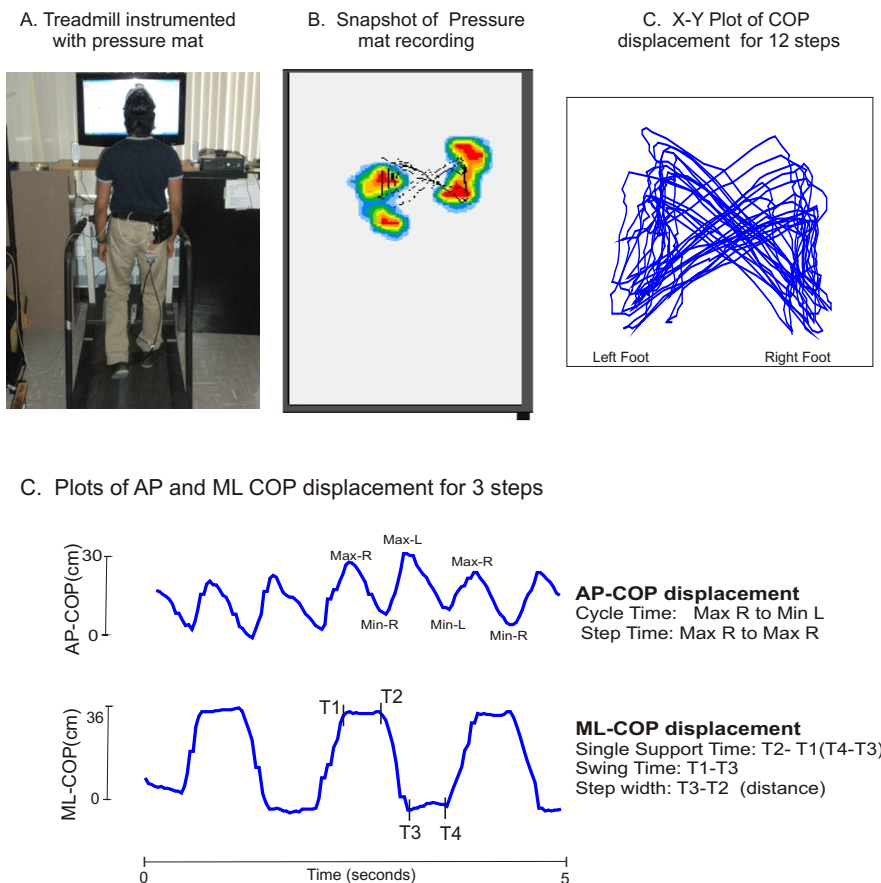


Figure 1: Experimental set-up. Panel A: A participant is shown walking on treadmill while viewing a computer monitor and using head rotation (motion mouse) to interact with computer tracking and cognitive tasks. Panel B presents a snapshot of left and right foot-ground vertical force profiles obtained during walking. Panel C presents X-Y plots of COP displacement for 12 steps. Panel D presents AP and ML COP time series data for 3 steps. Maxima and minima AP-COP excursion points for right and left steps are quantified, and used to compute swing and step times and step length. Start and end of plateau phases of ML-COP are quantified for right (upper plateaus) and left (lower plateaus). Single support times and step widths are then computed.

many walking stability indices have been proposed based on their associations with adverse health outcomes and falls, there is no commonly accepted criterion to define, much less to quantify, walking stability. Thus, addressing this momentous problem effectively requires developing sensitive, objective measures. Conventional spatiotemporal gait measures including step-to-step variability are parameters that provide a perspective on the consistency of the locomotor rhythm and

have been reported to represent walking stability^{31,37}. In recent years, there has been a shift to utilizing nonlinear dynamics tools to analyse walking stability. Among these tools being used are Lyapunov exponents and maximum floquent multipliers^{31,38}. Further work is underway to determine the optimal method to quantify walking stability and that can recognize clinically significant threshold anomalies in walking stability outcomes during multiple tasks.

- Computer-based therapeutic gaming tools: The TGP employs an inexpensive, commercial motion sense mouse to control and interact with any computer game or application. The motion-sense mouse (Gyration, SMK-Link USA) is small with inertial sensors which are used to derive angular displacement signals, and are used in a manner identical to a computer mouse to control position of the on-screen cursor. The motion mouse is secured by Velcro to a headband. With this simple method, seamless, responsive and high fidelity hands-free interaction with any computer application (custom or commercial exercise/brain fitness game) is made possible. Computer controlled goal-directed movements can provide an easily accessible way to track a wide range of cognitive events, and while performing complex motor behaviours such as walking (see Szturm et al. 2013)²⁷.

- Interactive computer applications: To automate monitoring of performance during interventions, a computer game with two assessment modules was developed: (a) visual tracking module and (b) cognitive task module. The details of the framework for a motion-sensor based gaming milieu are given in Szturm et al. (2011)³³. A computer-based Tele-rehabilitation platform where treatment and assessment are integrated is highly attractive for many reasons:

- (a) Cost effective, save time.
- (b) Documents volume of practice; provides measures of intensity, duration and compliance.
- (c) Immediate feedback for client and health care providers.
- (d) Monitors performance for each session, and thus can conduct trend analysis, and establish dose-response relationships.

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Visual tracking task module

This application was created to move an on-screen cursor (bright-coloured circle) either horizontally or vertically in a sinusoidal fashion (user defined frequency and amplitude). Two tracking tasks are available:

- (i) Closed loop tracking (with respect to head): In this task, two cursors of different colours appear on the monitor. One is the target cursor and the second cursor is slaved to head rotation via the head-mounted motion mouse. The task goal is to overlap the two cursors during the cyclic left-to-right cursor motion. In this task, foveation is necessary to determine the amount of overlap (error) between the target cursor and the head cursor.
- (ii) Open-loop tracking (with respect to head): In this predictable cyclic tracking task, only the target (computer) cursor is displayed, and participants are asked to rotate the head in concert with motion of the target cursor for 45 s. This task does not require continuous foveation to detect a position error, but head rotation is still required.

The coordinates of the computer cursor (reference target) and the user movements (head rotation via head mouse) are used to compute the coefficient of determination (COD) to represent the quality of tracking movements i.e. how well each participant followed the cyclic cursor motion. Figure 2 presents typical plots of cursor and actual tracking motion (observe difference) to illustrate the data analysis procedure.

Cognitive task module

A modified version of the UFOV has been designed to evaluate visual-spatial processing together with eye-head coordination. The test game is to move a paddle (game sprite) to catch falling bright circle objects (targets) moving vertically top to bottom, and to avoid other shape (or

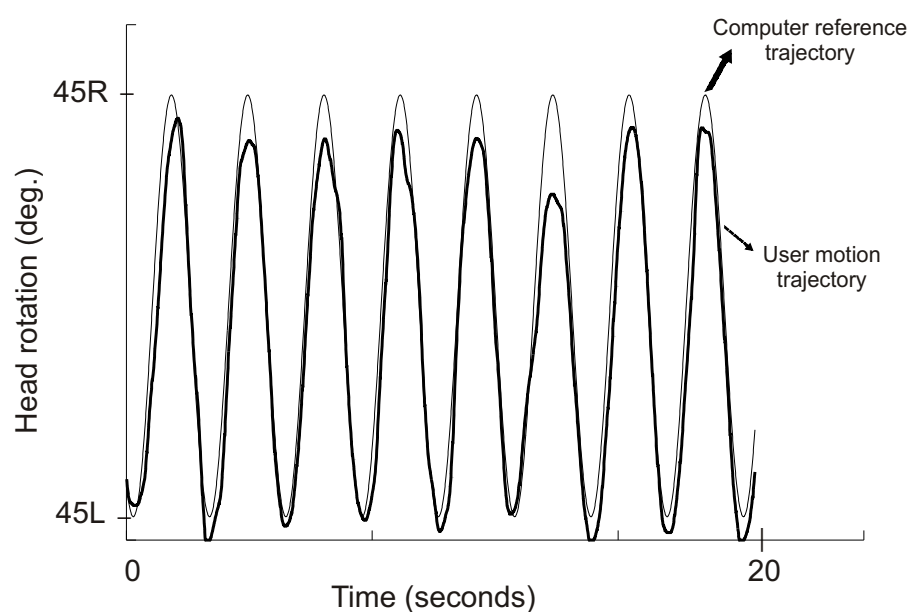


Figure 2: Synchronous plots of the reference cursor motion and user movement trajectories (head rotation) for a typical tracking task. Maxima are the left most position and minima the right most position. Residual difference between trajectories is used to compute coefficient of determination.

colours) game objects (distracters). The objects appear at user defined fixed intervals (e.g., 2 s) and at random locations on the monitor. The game is instrumented with an assessment module. This generates a logged game file recording (80 Hz) the following signals associated with player performance with respect to game events: (i) time index and coordinates of each game object and (ii) position coordinates of the game paddle (slaved to head rotation). Figure 3A presents trajectory of head rotation of one game file (obtained in standing) and Figure 3B shows all segmented game events within one trial. These contextual game events are sorted by direction and amplitude to obtain multiple event groupings with similar movement features (Figure 3C). For a full description, see Lockery, Peters, Szturm et al.³³ and Szturm et al.²⁷ features of the test game events provide a basis for objective quantification of cognitive functions, as illustrated in Figure 3D, which include (i) game success rate (percentage of target caught), (ii)

average motor response time (time from appearance of the target to start of the paddle movement), (iii) average movement execution time and (iv) movement efficiency.

Clinical applicability

Physical activity combined with cognitive enrichment has the potential to impact both the prevention and management of cardiovascular fitness, balance impairments, mobility limitations, decline in cognitive function and fall risk. Although various forms of balance and locomotor training have been evaluated, few studies have assessed the optimal timing, intensity and duration of the interventions (exercise and activities). The types and amount of cognitive stimulation participants engage in during intervention also needs to be measured, and this will help clarify the potential added benefit of activities beyond physical exercise. A blended analysis of balance, mobility vision and cognition will also contribute to a better understanding of the functional consequences of decline

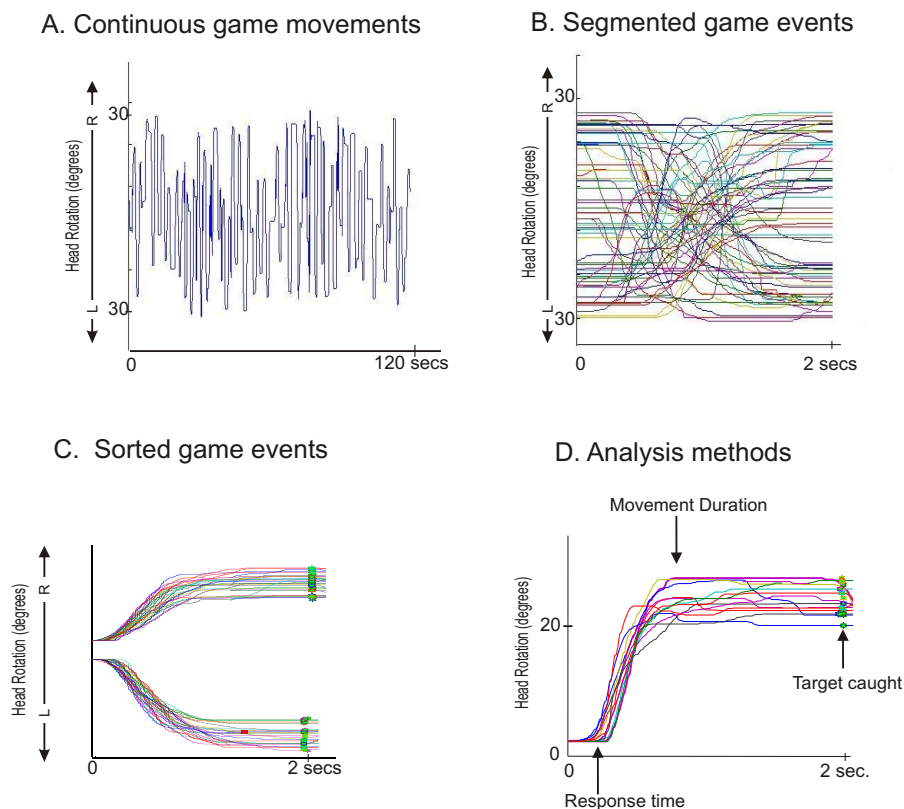


Figure 3: Panel A: The trajectory of game paddle movements (head rotation) for one logged game file, 120 s duration (x-axis). Each game event is 2 s in length; thus, recording includes a total of 60 game events. Panel B presents the overlay of individual game events segmented based on index times of target appearance and disappearance from player movements shown in panel A. Time zero is the onset of the target appearance (event onset), the end of the event is time when the target disappears. Panel C shows the segmented game events in Figure 1B, sorted and grouped in functional bins, which in this case represent medium amplitude player movements in the leftward direction (upward trajectories), and rightward direction (downward trajectories). Panel D illustrates the analysis methods to quantify response time and movement time from groupings of leftward, medium amplitude game events of one trial.

in physical and mental skills with age and in the early stages of disease, and this will help in making choices for prevention, treatments and lifestyle decisions. New Telerehabilitation technologies will likely improve clinical outcomes by making therapy more available, more motivating and more specific and effective. However, technology-assisted rehabilitation and cognitive enrichment is still a relatively young discipline. There is a need to develop and validate low-cost, engaging activity and cognitive platforms that can extend quality

health care to the community and ultimately the home.

It is important for middle aged and older adults to integrate and couple 'neural fitness' training in their typical aerobic and cardiac fitness training. Such a program is aimed at primary and secondary prevention of balance impairment, mobility limitations and cognitive decline with age. This would be in addition to rehabilitation for individuals with neurological disorders, e.g., traumatic brain injury, stroke, multiple sclerosis, Parkinson's, concussion and dementia.

Improved and cost effective methods of screening and fall risk assessment in the community linked with quality exercise and activity programs is important because continued difficulties and injuries will have a sizable impact in these large populations.

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