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Virtual Reality Applications in Improving Postural Control and Minimizing Falls

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Abstract- **Maintaining balance under all conditions is an absolute requirement for humans. Orientation in space and balance maintenance requires inputs from the vestibular, the visual, the proprioceptive and the somatosensory systems. All the cues coming from these systems are integrated by the Central Nervous System (CNS) to employ different strategies for orientation and balance. How the CNS integrates all the inputs and makes cognitive decisions about balance strategies has been an area of interest for biomedical engineers for a long time. More interesting is the fact that in the absence of one or more cues, or when the input from one of the sensors is skewed, the CNS "adapts" to the new environment and gives less weight to the conflicting inputs [1]. The focus of this paper is a review of different strategies and models put forward by researchers to explain the integration of these sensory cues. Also, the paper compares the different approaches used by young and old adults in maintaining balance. Since with age the musculoskeletal, visual and vestibular system deteriorates, the older subjects have to compensate for these impaired sensory cues for postural stability. The paper also discusses the applications of virtual reality in rehabilitation programs not only for balance in the elderly but also in occupational falls. Virtual reality has profound applications in the field of balance rehabilitation and training because of its relatively low cost. Studies will be conducted to evaluate the effectiveness of virtual reality training in modifying the head and eye movement strategies, and determine the role of these responses in the maintenance of balance.**

Keywords: Balance control; Head Movements; Multi-sensory Interactions, Virtual reality training.

I. INTRODUCTION

Falls and imperfect balance mechanisms are undesirable scenarios. These can cost hundred and thousands of dollars in health care and significantly affect the individual's quality of life. The human Central Nervous System (CNS) maintains posture and upright stance with the help of sensory inputs from vision, vestibular, proprioceptive and somatosensory inputs. Each input has its own function and provides information to the CNS based on its location. These various sources send their localized information to the CNS, and then the CNS allocates some weight to all these inputs, integrates them spatially and comes up with strategies for upright stance and posture control. However, under certain conditions like sudden perturbations, illness, or with old age, the sensory systems cease to be accurate. Under these circumstances the CNS adapts itself to the situation and gives less weight to the faulty or the conflicting inputs [1].

When in an unfamiliar environment or situation, we tend to make judgments and decisions based on past experiences that were similar to the situation at hand. However, if none are available then our senses adapt to the new situation. Studies show that adaptation helps in alleviating the conflicting cues and re-weighting of the sensory signals. The focus of this paper is to review some of the basic models put forward to explain these re-weighting strategies used by the CNS. It is important to mention here that for effective balance control, it is necessary for the sensory inputs to work in a set of feedback loops. For example, the visual inputs can confirm if we have taken a step in the right direction to avoid collision with an obstacle. So, integration and feedback forms the key issues in any model that explains the strategies of CNS for balance.

To see the impact of integration of sensory input and to better understand the adaptation process, various experiments have been performed. For example to see what happens when the vestibular cues are absent while all other cues are intact, the responses of patients with vestibular disorders are studied. Similarly, experiments are done where somatosensory cues are disabled by asking subjects to stand on a compliant surface, such as rubber foam. To disable proprioceptive cues, the 'body sway referencing' technique is often adopted. In this approach, the tilt angle of the support base is coupled 1:1 to body tilt angle. In these situations, it is seen that subjects rely more on visual inputs [2,3,4,5]. These findings clearly indicate integration and re-weighting of the inputs in the CNS.

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II. ROLE OF SENSORY INPUTS IN DETERMINING BALANCE AND SPATIAL ORIENTATION.

As discussed there are various sensory inputs that are responsible for our balance. The visual cues provide information about the position and motion of the head with respect to the surrounding and based on information in the visual surrounding, a reference for verticality. The main role of the proprioceptive and somatosensory system is to provide a relationship between the body segments with respect to one another (limb position) and to sense the distributed tactile input stimuli at the neural level respectively. The vestibular system (located in the inner ear) keeps tabs on the motion and position of the head in space. It consists of otolith organs, which detect the linear acceleration and gravity, and three semicircular canals, which detect the angular acceleration of head. Fig 1 shows a simplified representation of a human motion control loop put forward by Bos et al (2002). For effective control of motion and balance, feedback is critical as it confirms if an intended motion is achieved or not [6].

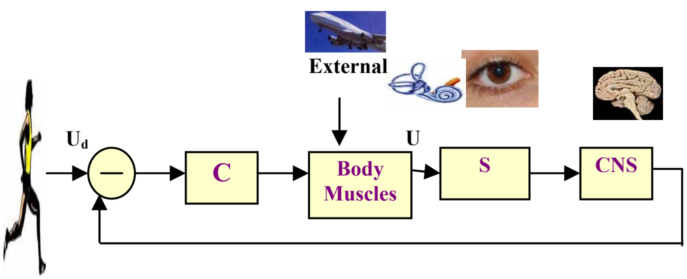

Figure 1: A simplified representation of the human motion control loop. U_d represents a desired body state; it directs the controller (C) within the Central Nervous System (CNS) generating motor commands that drives the muscles of the body. External sources like an aircraft can also move the body. The actual state of the body (U) is registered by (among other things) the vestibular apparatus and the visual system (S). The signals from these sensors are processed by the CNS for comparison with the desired body state. Adapted from Bos et al.

III. EXPERIMENTAL PROTOCOL

How the Central Nervous System interprets the cues coming from all sensory inputs for postural stabilization has been explained with the help of various models. The underlying principle of all these models is that the CNS allocates different gains or weights to the inputs to come up with balance strategies. The hypothesis that these strategies can be optimized to reduce the number of falls in individuals will be experimentally evaluated. Specifically, a virtual reality environment very similar to a desired occupational setting will be used. Encouraging the subjects to initiate head movements more often in the virtual environment can help to achieve this goal. The contribution of eye movements in avoiding falls and regaining balance will be studied. Also, the effect of target distance during balance perturbations on reducing or avoiding falls will be assessed. To do so, the subjects will be asked to look at a fixed point on the wall (while the distance of the target will be varied from 20 cm to 100 cm) while trying to maintain their balance under sudden perturbations. The postural sway can also be measured using foot pressure sensors provided in the sole of special footwear [7].

The experiment can be described in the following way (Figure 2): Healthy subjects (excluding anyone with vestibular disorders and vision problems), will be asked to complete a questionnaire (Berg Balance scale) and functional reach test to find out about susceptibility of falling, The strategies used by the subjects are evaluated while trying to maintain balance on a balance board (in different visual conditions), and by measuring postural sway before the experiment using foot pressure sensors, This will be followed by training in a virtual reality environment, while recording eye and head movements, and the effect of target distance (by asking the subjects to fixate their gaze on near and far targets while the virtual reality environment is in motion) is also included. The effect of the training will be evaluated by comparing the amount of postural sway and balance strategies before, during and after the training.

The results will help to determine whether virtual reality training will help to train the individuals with a history of falls or with susceptibility of falls to re-weight their sensory cues and to give less weight to the conflicting inputs.

IV. HOW BALANCE STRATEGIES DIFFER IN YOUNG AND OLD ADULTS

With age, in normal elderly adults, the visual, vestibular, neural and the musculoskeletal systems deteriorate. Studies show that the elderly rely on visual information more often for postural stability, although they have a tendency to initiate less head movements [8]. Older adults are more likely to take multiple steps to recover balance than younger adults or to reach to grasp objects for support [9,10,11,12]. Older adults rely more on visual information to maintain their balance or to recover their balance [13]. These findings suggest that if the older subjects have a solid understanding of their environment, then they know where to look for support. This may result from scanning of the environment when posture is stable and hence emphasizes the role of head movements in elderly. Visual inputs are affected by eye stabilization, which is controlled by the vestibulo-ocular reflex. Combined head and eye movements can be required to place objects of interest on the fovea.

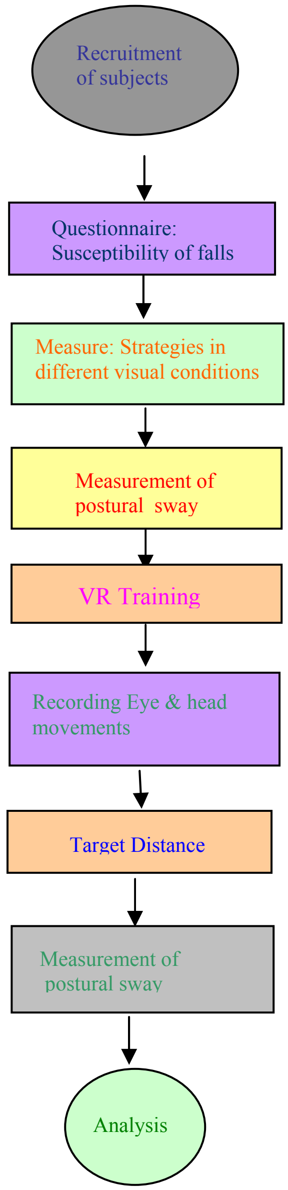

Figure 2: Experimental protocol. Step by step description of experimental set up to train individuals with history of falls or susceptibility of falls. For details refer to text.

Therefore it would be expected that an attempt to regain balance would employ the strategy of head and eye movements to assist in adjusting stepping and grasping reactions even with a longer latency. Additionally, active head movements would provide cues about self motion overlayed on the perturbation, potentially helping to calibrate or interpret the nature of the perturbation. Finally, active head movements would compensate for the inadequacy of somatosensory inputs. It is therefore surprising that older adults tend to move their heads less during postural perturbations than younger adults, and even younger adults do not tend to use this strategy to regain postural stability (Zettel et al., '05 and personal communication). Zettel et al. suggest that sufficient information is retained in a remembered spatial map of the surroundings, and that head and gaze shifts are avoided to permit attention resources to be focused on the task of balance recovery. Also, in patients with vestibular disorders, in rehabilitation programs, the importance of head movements is emphasized. They are encouraged to move their heads more often as it facilitates the adaptation process and more weight is given to the visual inputs while doing so thereby compensating for the impaired vestibular inputs [17].

V. APPLICATIONS

The concept of re-weighting of the sensory inputs finds applications in balance rehabilitation. To treat patients with vestibular disorders, researchers often suggest physical exercises. Interestingly, but not surprisingly, Virtual Reality (VR) is being evaluated for balance rehabilitation. The idea of using VR in rehabilitation comes from the fact that dynamic visual inputs can induce body sway in subjects. The amount of body motion experienced by the subjects also depends on the field of view. More immersive environments have larger field of view. Keshner and Kenyon (2000) demonstrated in their experiments that during quiet stance, when subjects were exposed to complex or simple stereo visual rotation scenes, the upper body responded to visual-vestibular signals whereas the ankle responded to proprioceptive inputs [14,5]. Virtual reality provides an ideal environment very similar to the real world to understand the balance strategies employed by the CNS, and also helps to differentiate the behavior of various sensory inputs. It is convenient to implement because of its low cost. Also, in VR, the simultaneous effect of various sensory modalities and neural responses can be studied together and in isolation, and hence might not mimic the real world response. Virtual reality has been used to increase head movements in patients with vestibular disorders so that more weight is given to the visual inputs [17]. To study the biomechanical and physiological response of the inputs, an immersive environment is used, and postural sway is measured using force plates or by measuring head or eye movements depending on the need of the situation. Based on the models, and studies in balance rehabilitation, it is proposed that virtual reality can help in reducing the number of occupational falls. Depending on occupational requirements and fall history of the workers, virtual reality training can provide a solution to re-weight individual's sensory inputs and hence minimize falls in workplace.

There is a high dependency on visual cues and low use of proprioceptive cues in subjects with a history of falls in an occupational setting (nurses in a hospital) [15]. Also, amateur soccer players rely more on visual inputs to maintain their balance as opposed to professional players. As a consequence amateur players fall more often [16]. In these conditions where workers rely more on visual inputs, it is proposed that virtual environments could help in developing adaptative strategies which will enable them to rely more on vestibular and proprioceptive information, and reduce the likelihood of falls.

VI. Conclusions and Future research

This paper discusses how various senses play an integral role in maintaining balance and how different gains or weights are allocated to these senses by the CNS. The allocation of different gains to the sensory inputs by CNS can be exploited to help adapt in conditions where one or two sensory inputs are not functioning properly. We proposed that such an adaptation can take place in everyday life or in a virtual environment. By using a virtual environment, a variety of individuals could be treated: people who might be afraid of falling or who have history of falling in real world situations such as the workplace, and even older adults. A study that can determine the role of active and passive head movements and binocular gaze responses during balance control in normal subjects as well as in those with a history of falls is described. The experiments will evaluate the ability of virtual environments in training or modifying these responses. The head and eye movements of the subjects will be recorded and measured to understand the strategies employed by them. The testing of head movement strategies is postulated to be an important factor for understanding the way that different populations recover balance, and in the development of prevention strategies. It is also hypothesized that by investigating the eye and head movements of the elderly and young adults, better models and better virtual rehabilitation environments can be developed that will improve balance disorders in the elderly and in subjects with vestibular disorders.

Virtual reality can also provide a solution in reducing work related falls. It is believed that this could occur by re-weighting the sensory cues that are responsible in maintaining balance and orientation in a workplace setting.

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