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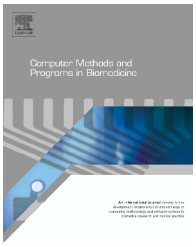

# Machine learning-based assessment tool for imbalance and vestibular dysfunction with virtual reality rehabilitation system

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## ABSTRACT

*Background and objective:* Dizziness is a major consequence of imbalance and vestibular dysfunction. Compared to surgery and drug treatments, balance training is non-invasive and more desired. However, training exercises are usually tedious and the assessment tool is insufficient to diagnose patient's severity rapidly.

*Methods:* An interactive virtual reality (VR) game-based rehabilitation program that adopted Cawthorne–Cooksey exercises, and a sensor-based measuring system were introduced. To verify the therapeutic effect, a clinical experiment with 48 patients and 36 normal subjects was conducted. Quantified balance indices were measured and analyzed by statistical tools and a Support Vector Machine (SVM) classifier.

*Results:* In terms of balance indices, patients who completed the training process are progressed and the difference between normal subjects and patients is obvious.

*Conclusions:* Further analysis by SVM classifier show that the accuracy of recognizing the differences between patients and normal subject is feasible, and these results can be used to evaluate patients' severity and make rapid assessment.

## 1. Introduction

Vertigo is a disorder prevalent in the general population. According to the study of Lai et al., the prevalence of vertigo is around 3.13 per 100 adults. The prevalence and recurrence of vertigo increased significantly with age [1]. Vestibular dysfunction usually leads to dizziness [2]. Common types of dizziness are the Meniere disease, benign positional vertigo, vertebrobasilar insufficiency, vestibular neuritis, and sick

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headache. Dizziness may persist for minutes, hours, or even longer; and consequently it interrupts people's daily routines and affects their quality of life. During episodes of dizziness, people may experience shaking, tilting, and difficulty in standing; and because they may sense motion when no motion is occurring relative to the earth's gravity, this makes them prone to fall [3–5]. Therefore, dizziness may be severely dangerous to people who might be holding a glass or knife in the kitchen or standing in the bathroom. Worst of all, dizziness will worsen if left untreated.

Common treatments are vestibular surgery, drug treatments, and balance training exercises. Research has revealed that the combination of these treatments can effectively reduce dizziness [6]. Compared to surgery and drug treatments, balance training is non-invasive and generally suitable for a majority of patients. The Cawthorne–Cooksey exercises are a set of exercises that improve patients' balance by training their ability to control their eyeball movements and head movements, extremity stretching, and bilateral body balance. Repeating these exercises should enhance patients' cervico-ocular reflexes, which would help them retain balance during episodes of dizziness [6,7]. The Cawthorne–Cooksey exercises require participants to move their eyeballs without moving their head, move their head without changing their body position, rotate and bend their body using the force of the waist, rotate their head and shoulders using the force of the shoulders, and throw and catch objects with both hands. These exercises are usually time-consuming and tedious because they need to be repeated multiple times. Furthermore, it is difficult to customize the exercises for individual patients because the differences among patients are not quantifiable.

To overcome the limitations of the traditional training methods, an interactive virtual reality (VR) game-based rehabilitation program and sensor-based recording system were introduced [3,8–11]. These integrated systems not only motivated patients to exercise regularly, but also quantified the rehabilitative process into meaningful balance indices [12,13]. In addition, VR technology makes the games more enjoyable and more similar to daily life. Physical therapists can adjust the game's contents and difficulty level based on the patient's life experiences. Along with advances in vision-based technology, the optical tracking and skeleton-detection libraries provided by Microsoft Kinect captures an abundance of human motion data. These camera-based recording systems largely reduce the need for manual interference in the rehabilitative training process. Full rehabilitation systems should be able to provide immediate visual, auditory, and tactile feedback to encourage patient-involvement and improve training effectiveness.

A game-based method has been used for the rehabilitation of neurological conditions [16–20], musculoskeletal disorders [21–23], or elderly adults [24–26]. However, few studies have used video games to assess balance levels [27]. The VR gives the system unique advantage by providing the 3 dimensional environments for imbalance patients to re-gain their balance capability. A previous study of patients with a heterogeneous history of lower extremity injury showed that their balance activity scores demonstrated a poor correlation between the center of pressure outcomes and the Star Excursion Balance Test reach distances [27]. This study used VR video games that adopted Cawthorne–Cooksey exercises and machine learning-based classifiers as a balance assessment tool for people with vestibular dysfunction. The classifiers were trained and cross-validated with features such as center-of-pressure trajectory and self-calculated variables of interest. The consistent findings between the performance data and balance assessment measurements suggest that this VR game-based exercise may be applicable to the clinical assessment and rehabilitation of people with vestibular dysfunction. The objectives of this study are to validate a VR system that can be used for imbalance patients rehabilitation.

## 2. Methods

### 2.1. *Preliminaries*

#### 2.1.1. *Cawthorne–Cooksey exercises*

Traditional Cawthorne–Cooksey exercises can be categorized into a series of 7 movements: eyeball movements, head movements, waist rotation movements, stooping down movements, shoulder rotation movements, body rotation movements with eyes closed, and the ball throwing test. In the eyeball movement exercise, subjects are requested to look up and down, left and right, and stare at their index fingers while their fingers move slowly then quickly, and move up and down, left and right, and forward and backward. Their head should not move during these eye movements. The head movement exercise requires subjects to lean forward and backward without losing balance, and turn their head to the left and then to the right. Then subjects are requested to rotate their waist with their shoulders hunched up in the waist rotation movement. In the stooping down exercise, subjects are requested to pick up light objects from the ground. Then subjects are requested to rotate their head and shoulders with their eyes open and then closed. Lastly, subjects are requested to throw a tennis ball back and forth between both hands. Both hands should be placed at eye level so that their eyes keep track of the ball.

#### 2.1.2. *Balance index: Statokinesigram (SKG)*

Measuring the center of pressure is a common method used to quantify balance. Similar to the clinical used posturography, a statokinesigram (SKG) is derived from a time-series recording of the center of pressure that is built in the Wii Fit program. By plotting the time series of the center of pressure in a 2D scatter plot, an envelope area can be visualized to represent the distribution of the body balance. The SKG is the envelope area. The SKG-calculation method adopted in this research is based on convex hull calculation: a minimum convex polygon search algorithm to enclose all center-of-pressure records. For example, if a healthy subject were requested to stand still, the convex hull/SKG area would be small. However, this may not be the case for patients with vestibular dysfunction. Therefore, the SKG could be an important index to assess body balance. In addition to the SKG index, multiple balance indices could be derived from the SKG, such as the maximum mediolateral (maxML) and anteroposterior (maxAP) trajectory excursions, mean mediolateral (meanML) and anteroposterior (meanAP) trajectory excursions, and the standard deviation of mediolateral (meanML) and anteroposterior (meanAP) trajectory excursions. These derived indices