# Juggling on The Moon: A VR System for Complex Motor Skill Learning

**Hiroyuki Kambara[1,2], Wanhee Cho[2], Hyeonseok Kim[3], Rikiya Oya[1], Yusuke Kitami[1], Makoto Kobayashi[2], Supat Saetia[2], Takahiro Kagawa[4], Hirokazu Tanaka[5], Makoto Miyakoshi[3], John Iversen[3], Scott Makeig[3], Makoto Sato[2], Natsue Yoshimura[2]**

h.kambara@eng.t-kougei.ac.jp
[1] Tokyo Polytechnic University, Atsugi, Japan
[2]Tokyo Institute of Technology, Yokohama, Japan
[3]University of California San Diego, La Jolla, US
[4]Aichi Institute of Technology, Toyota, Japan
[5]Tokyo City University, Setagaya, Japan
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**ABSTRACT**

*Motor skill training systems based on virtual reality (VR) technologies are becoming more popular in sports training, entertainment, and rehabilitation. In this paper, we will introduce a VR ball-juggling system composed of SPIDAR-W haptic device and a head-mounted-display. The results of juggling training using the VR system will be presented.*

## 1 Introduction

Recent advances in virtual reality (VR) technology have made motor skill training using VR more popular in sports training, entertainment, and rehabilitation. One of the advantages of using VR is that training parameters and feedback on motor performance can be easily manipulated to make beginners or patients motivated for training. However, training in a VR environment does not necessarily lead to the improvement of motor skills in the real environment because of the lower fidelity of VR environments to the real one. It has been suggested that the lack of haptic feedback especially prevents motor skill transfer from the virtual to the real world [1]. Meanwhile, introducing a haptic device into VR training makes the system expensive and limits its use. In addition, due to the spatial limitation of haptic devices, the types of motions were limited to relatively simple exercises such as reaching and grasping [2].

Here, we will introduce a new VR system realizing complex motor tasks such as ball juggling with the haptic feedback. Recent neuroscientific research indicated that a few months of juggling training cause changes in brain structure [3,4] and neural connectivity [5] for not only young but also elderly people [6]. Meanwhile, juggling tasks, even for the basic trick like the 3-balls cascade pattern, would be difficult to learn for beginners in the real environment since it requires complex coordination between eyes, both hands, and balls within a fraction of the time before a ball hits the floor. Our VR juggling system can ease the difficulty of juggling by manipulating the physical parameters in the VR world and have the possibility to enhance motivation to keep training for beginners. In this paper, we conducted an experiment to train juggling beginners using our VR system and investigated whether VR juggling training leads to better juggling performance in the real environment.

## 2 Method

### 2.1 VR Juggling System

The VR juggling system is composed of a haptic device, a head-mounted display (HMD), and a computer to control the devices (Fig. 1). The haptic device, named SPIDAR-W [7], is one of the applications of SPIDAR series [8] and manufactured by ARACHNOFORCE Inc. The haptic device is wearable and able to apply 3-D

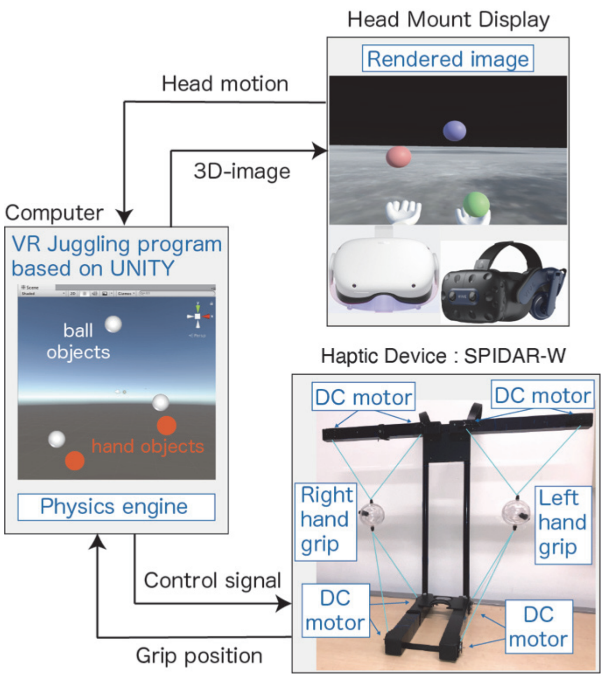


**Fig. 1 VR juggling system configuration.**

translational force to both of the user's hands by the motors controlling the tension of the strings attached to spherical plastic grips. In addition, the position of the center of the grips is computed from the length of each string measured by encoders. The control signal and grip position information are sent through a USB cable between the haptic device and a computer with 1k Hz.

The VR juggling application was made with UNITY game engine. In addition to the gravitational acceleration, the physical properties of the balls, such as size and mass, can be changed by experimenters or users to match their aims. We also introduced the parameter to scale the initial velocity of the ball after being released from the hand. This parameter is adjusted to prevent the balls from flying too far under small gravitational acceleration. The downward force was applied to the user's hand when the ball is held in the virtual hand. Its magnitude is computed by multiplying the mass of the ball and the gravitational acceleration. The visual image of the balls and the hands is displayed by an HMD to preserve depth cues to assist in sensing the relative position of the balls and the hands. Although the HMD could be either of HTC Vive Pro series or Oculus Rift/Quest series, we used HTC Vive Pro-Eye in the VR training experiment. The balls are supposed to be contacted with the hands when the distance between the hand and the ball got smaller than the sum of the radius of the ball and the hand. The balls are held in the hand when the button attached to the grip is pressed by the user and will be released in the air when the user stops pressing the button.

### 2.2 Juggling Training with VR Juggling System

In order to verify the effectiveness of the VR juggling system, we conducted experiments in which subjects learned juggling in the VR environment.

The subjects were two healthy young persons who hand no experience of juggling before this experiment. They were asked to learn a 3-balls cascade pattern which is a basic juggling trick. The total training period was 10 days. On each day, the subjects had 20 minutes of VR juggling session to practice a 3-balls cascade pattern using the VR juggling system (Fig. 2). In addition, to evaluate juggling skills in the real environment, the subjects had real-world sessions before and after the VR juggling session. In the real-world sessions, subjects performed a 3-balls cascade pattern with real balls. The duration of each of the real-world juggling sessions was 5 minutes except for days 1, 5, and 10 in which the duration was set as 15 minutes to record EEG (electroencephalogram) signals. We recorded video and motion capture data to analyze the juggling performance of the subjects. The experimental protocols were approved by the ethics committee of the Tokyo Institute of Technology (approval no. 2020107).

(A) VR juggling session (B) real-world session

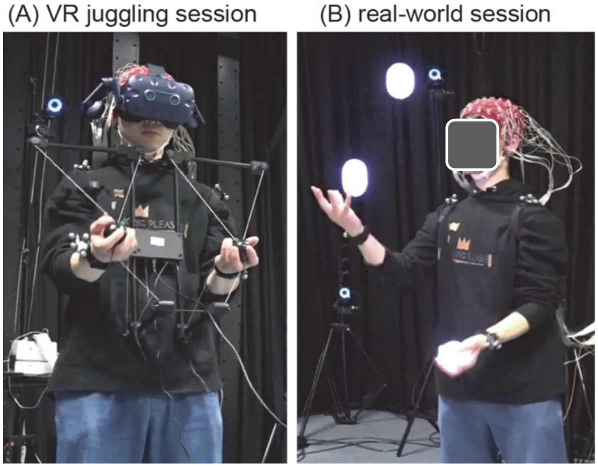

**Fig. 2 Experiment sessions.**

## 3 Results

To evaluate the juggling skills in the real world, we counted the number of consecutive throws that subjects could make in each trial during the real-world sessions. We then computed the average of the five highest number of consecutive throws within each of the real-world sessions (Fig. 3(A)). We also computed the mean of the top five throwing counts among the real-world

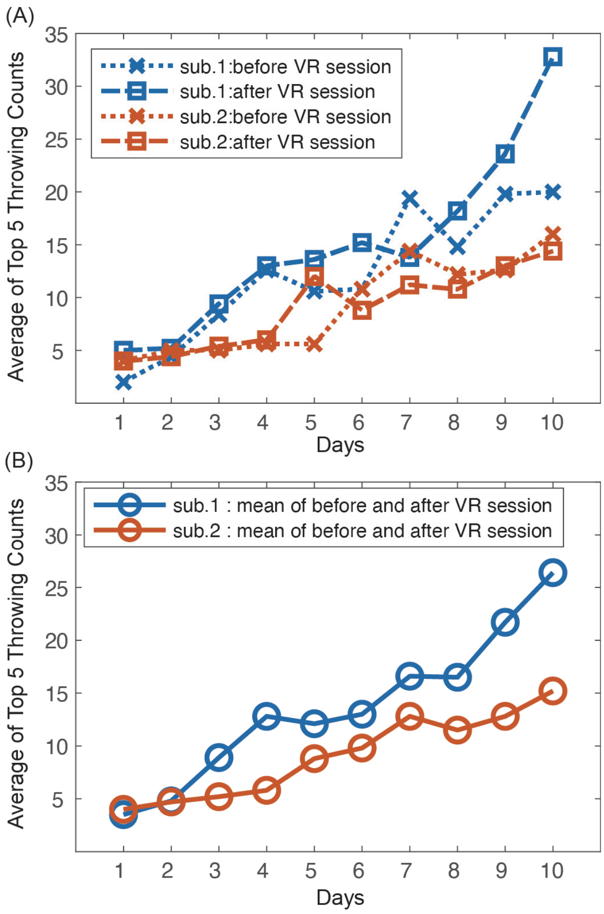


**Fig. 3 Juggling performance in the real-world.**
(A) Average of top 5 consecutive throwing counts within before and after VR session. (B) Average of before and after VR sessions.

sessions on the same day (Fig. 3(B)).

Although there are a few sessions where the average throwing counts were reduced from the previous day, we can see substantial day-by-day improvements in the throwing counts for both of the subjects. We also can see that average of the top five throwing counts got larger in the session after the VR session than in the session before the VR session on most of the days for subject 1. However, this trend did not hold for the other subject.

## 4 Discussion

In this study, we were able to observe day-by-day improvement of juggling skills in the real world for both of the subjects. Since the experimental design allowed the subjects to experience 3-balls juggling with real balls, we cannot directly confirm that the training with the VR juggling system induced the improvement of juggling skills in the real environment. However, there seems a possibility that the subjects in this study learned the juggling skills faster than the subjects who trained only in the real world. In the past study [9], most of the subjects who never experience juggling before the training only achieved at most eight consecutive throws after 3 hours of training of the 3-balls cascade pattern in the real world. On the other hand, in this study, both subjects experienced total of 160 minutes of juggling in the real world and became able to throw the balls more than fifteen times consecutively. In another past study [10], juggling beginners needed at least 1 hour, and at most 2 hours or more, of juggling practice to become able to make 4 consecutive catches (which corresponds to 5 consecutive throws). In this study, both subjects needed 50 minutes of real-world juggling experience before they can throw the balls more than 5 times consecutively. Although we need to correct data from more subjects, we believe that training in the VR environment contributed to the improvement of the juggling skills in the real environment.

In addition to the VR juggling system introduced in this paper, several other applications have been developed that allow performing juggling in the VR environment. For example, there is commercial software for VR juggling for Meta Quest 2 system [11]. In addition, virtual juggling software using the VIVE Pro system has been developed [12]. The advantage of our system over these existing applications is the ability to give haptic feedback when the user is grabbing the ball in the virtual environment. As we mentioned in the introduction, the lack of haptic information in a VR environment is suggested to be a critical factor that avoids the transfer of motor skills from the virtual to the real world. It is our future work to verify how the presence or absence of haptic information during VR juggling training affects the juggling skills in the real world.

## 5 Conclusions

In this paper, we introduced a new VR system realizing complex motor tasks such as ball juggling with the haptic feedback. We also conducted the experiments to verify the effectiveness of our VR juggling system for learning juggling skills in the virtual environment. The subjects were asked to practice the 3-balls cascade pattern in the virtual world by using our VR juggling system. We observed substantial amount of improvement in the juggling performance in the real world after 10 days of practice in the VR environment. Our future work is to correct more data from other subjects and verify the effectiveness of the system statistically.

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