Designing for Children
- With focus on 'Play + Learn'

Development of An Assistive Haptic Device for Refinement of Motor Skills in Children.

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Abstract: Children who have lost the use of their fine motor skills have traditionally relied on occupational therapists for specialized training and assistance needed to overcome their disabilities. However, conventional therapy is expensive, monotonous and instills a feeling of embarrassment in children owing to their constant dependence on the therapist. As an alternative, robot-assisted training has great potential for rehabilitation and refining of motor skills as it is highly accurate and can be sustained for prolonged periods of time. This paper presents the design and development of HapKid, a 2 Degree-of-Freedom haptic device possessing a pantograph structure and equipped with low-cost motors and encoders which enable it to effectively apply corrective forces to the user's hand during training. In order to retain the child's interest in therapy, HapKid is augmented by immersive game-like virtual environments possessing auditory and visual feedback and hence giving the device a great advantage over conventional therapy.

Key words: Haptic, Motor Skill Rehabilitation, Pantograph, 3D Printing, Virtual Environment.

1. Introduction

Children perform a multitude of tasks with the help of their hands throughout their school day. Starting with demonstrating pencil skills of writing and drawing to opening lunchboxes, children make efficient use of the small muscles of their hands. The skills acquired by the efficient usage of these muscles are termed as fine motor skills and are essential for performing everyday self-care tasks as well as academic ones. Hence, children suffering from fine motor skill deficits face significant disadvantages in the classroom as well at home. Without the ability to accomplish everyday tasks with ease, their quality of life gets affected which consequently affects their self-esteem in addition to compromising their academic performance.

Developmental Coordination Disorder (DCD) is the failure of children to acquire age appropriate motor skills without any apparent cause. It is estimated that about 6% of children in primary schools are diagnosed with DCD and face significant difficulty in using both their hands for acts of daily living involving object manipulation, hand-eye coordination and proprioception or body awareness (Widiger et al., 1996). A study conducted to estimate the occurrence of Developmental Coordination Disorder among school children in the Loni town of Maharashtra, India, revealed a 30% prevalence of indication of the disorder (Tawade et al., 2019).

In order to mitigate the effects of this disorder and improve the quality of life, children are assigned an Occupational or Physical Therapist. Despite the success of traditional Physical Therapy, it has not been a very popular option among school children as it leaves the children feeling psychologically distressed and low on self-esteem due to a constant dependence on another person. Also, occupational therapy is quite expensive for the family. As an alternative, robot-assisted training has been found to have great potential for rehabilitation and refinement of motor skills. Robotic training has the advantage of being highly accurate, producing a wide range of adjustable forces, capable of measuring progress automatically and most importantly, can be sustained for long periods of time with the advent of game-like virtual reality environments that keep the patient immersed in therapy (Patton & Mussa-Ivaldi, 2004).

Towards the realization of the above-mentioned advantages of robot-assisted therapy, this paper presents the design and development of the HapKid robotic device for rehabilitation of fine motor skills in children. The idea behind the design of HapKid is that children be relieved of their dependence on therapists to some extent and rehabilitative devices for them be designed to meet specific needs of being accurate, effective and immersive. The device has a small structure, made of simple linkages and augmented by virtual-reality environments that can retain the children’s interest in therapy for prolonged periods of time.

2. Design Overview

Several challenges are faced by the designer of a haptic device. The important feature of designing the device specifically for children adds its own set of complexities. Essentially a human-machine interface, the haptic device must possess an ergonomic design with a compact structure such that its operational workspace is larger than the device itself. Thereby allowing the child to freely explore the workspace with minimal spatial intrusion. Furthermore, the response of a haptic device mainly involves replication of mechanical impedances as generated by the virtual environment. These impedances vary widely in the physical world and hence the designer faces a great challenge in programming the device in such a way so as to exhibit a comparably broad range of such impedances. Such a haptic response ensures the child gets a realistic ‘feel’ of the forces (Hayward et al., 1994). The following section explains the mechanical, electrical and interface design aspects of the HapKid.

2.1 Mechanical Design

HapKid is intended for the rehabilitation of children suffering from motor deficits due to neurological injury or genetic factors. Such children mostly grow vary of conventional therapy and eventually give it up midway owing to boredom, lack of motivation and embarrassment in front of peers (McCarthy et al., 2016).Therefore, the mechanical design of HapKid presented here is such that it falls within the dimensions of a table-top device taking as little a space as any average sized book or clipboard. This will allow the children to treat HapKid as just another addition to their writing desk or work bench serving as an interactive supplement to conventional therapy.

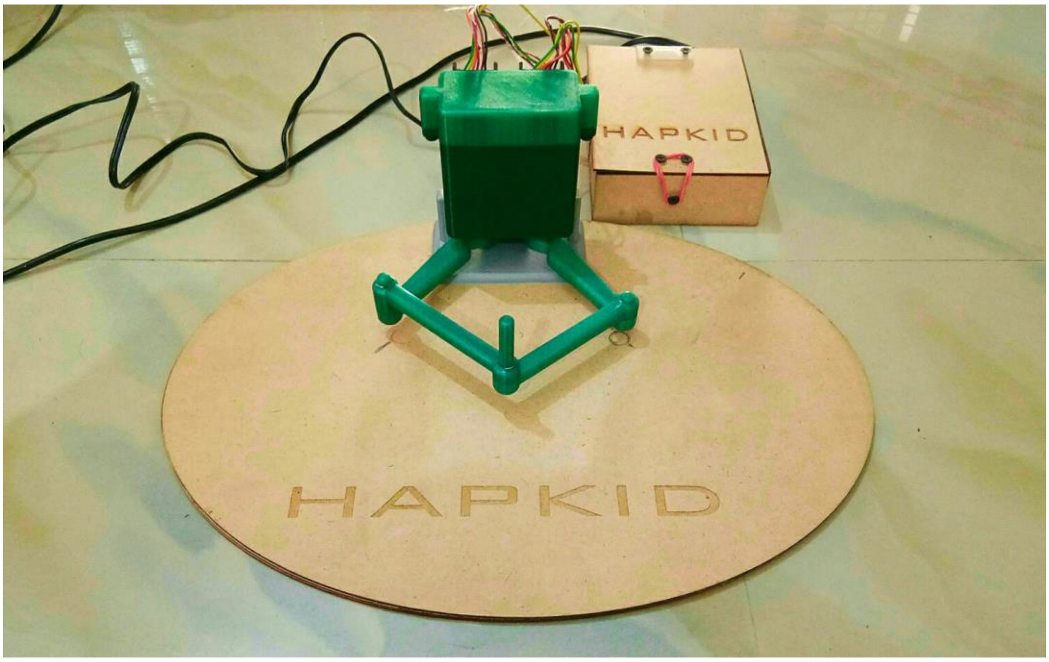

Figure 1. HapKid – A 2-DOF Haptic Device.

For maintaining the simplicity in design and as a preliminary effort towards refinement of fine motor skills using a haptic device, the HapKid has been developed with a pantograph planar structure having only 2 degrees of freedom. As a 2DOF pantograph device, HapKid can access any coordinates in the X-Y plane thereby enabling the user to follow a desired trajectory and replicate various planar motions. Many previously developed haptic devices use the pantograph structure mainly for its magnification properties. One of the first haptic configurations to make use of the pantograph concept was developed by Vincent Hayward et al. in 1994 and the basic design is still being used in many recent devices such as the HapticKnob (Dovat et al., 2006).

HapKid is essentially a pantograph consisting of four 3D printed links (each having a length of 10 cm) with one of the links grounded as shown in the Figure 1. To the grounded link is connected the position sensor and actuator housing which is adjustable for the user's convenience. It rests on an elliptical base with the electronic circuitry housed in a small rectangular box.

One of the ends of both link 1 & 2 is attached to motors A&B respectively and their other end forms a linkage with links 3 and 4 which in turn combine to serve as an end effector which the user can grasp while performing the therapy. The end-effector can be customized as per the requirement of the exercise being practised e.g. practising letters with a pen shaped end-effector or as a joystick for trajectory tracing. The device developed in this paper is relatively small, having a workspace of about 80mm x 40 mm.

First, we used the forward and inverse kinematics of the device to design a linkage capable of reaching the entire workspace. The grounded link is 3.8 cm and the moving links are 10 cm each. The linkage is shown below at the four extremes.

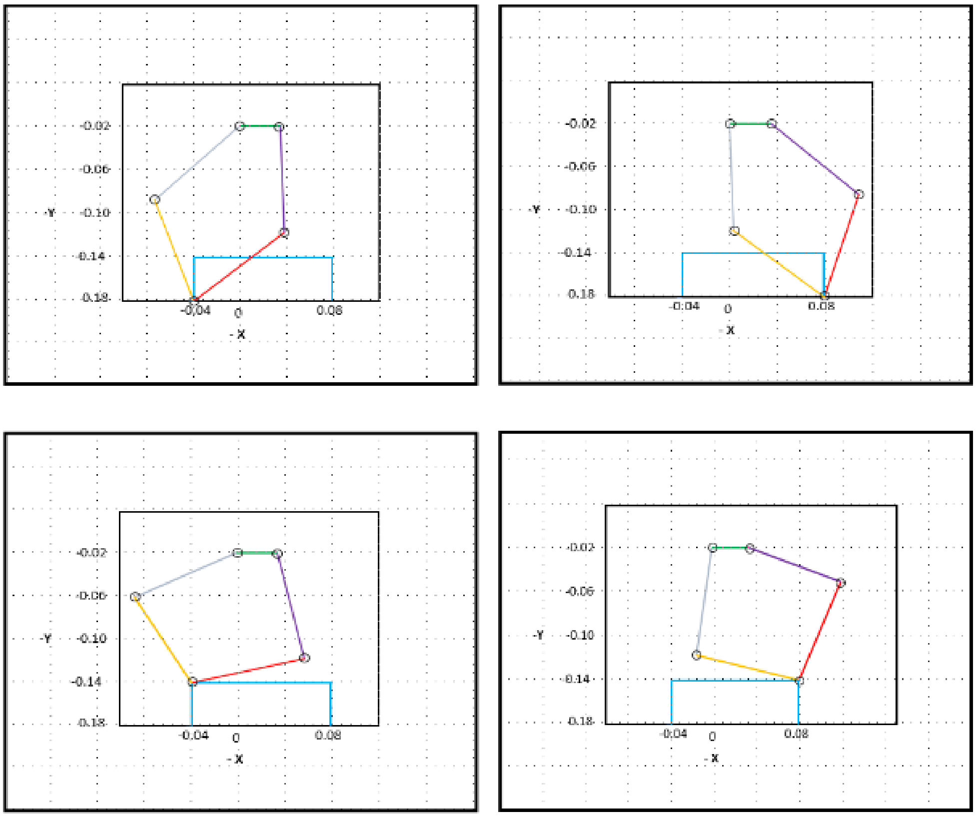

Figure 2. Linkage at extremes of workspace (in metres).

2.1.1 Device Kinematics

We derived the kinematics for HapKid from The Pantograph Mk. II - A Haptic Instrument (Campion et al., 2005). The direct kinematics problem consists of finding the position of point P_3 from the two sensed joint angles θ_1 and θ_5. The base frame is set so that its z axis passes through P_1. It was in the past solved using various approaches, the latest provided by Dovat et al., 2006. These approaches all share the observation that P_3 is at the intersection of two circles, the centers and the radii of which are known.

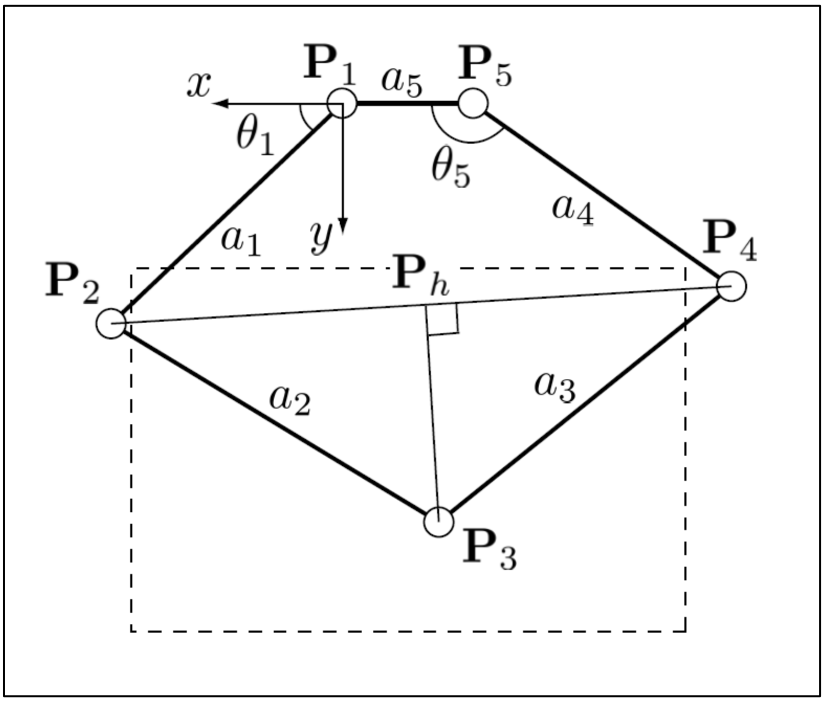

Figure 3. Diagram of the pantograph. (Campion et al., 2005)

The circles of radii a_2 and a_3 are centered at:

$$P_2\ (x_2,\ y_2) = [L * \mathrm{Cos}(\theta_1),\ L * \mathrm{Sin}(\theta_1)] \quad (1)$$

$$P_4\ (x_4,\ y_4) = [L * \mathrm{Cos}(\theta_5) - L5,\ L * \mathrm{Sin}(\theta_5)] \quad (2)$$

and intersect at two points corresponding to two configurations. The device, however, always operates in the configuration that has the largest y. We used a geometric approach to find x and y. Let P3 (x_3, y_3) and P_h (x_h, y_h) be the intersection between the segment P_2P_4 and the height of triangle $P_2P_3P_4$. The end effector position P_3 (x_3, y_3) is then given by:

$$x = x_h + (P3 - P_h / P_2 - P4) * (y_4 - y_2) \quad (3)$$

$$y = y_h - (P3 - P_h / P_2 - P4) * (x_4 - x_2) \quad (4)$$

2.2 Fabrication

Towards realization of the design, a CAD model of the device was developed in Autodesk Inventor 2017. The device was later fabricated with 3D printing facility available at Design Innovation Centre, Islamic University of Science & Technology, J&K. The 3D printed nature of this device makes it lightweight which is an important requirement of a haptic system, as weight of the device is perceived by the user as weight of the virtual or teleoperated environment and may spoil the user's experience of interacting with virtual objects through the haptic interface (Hannaford & Okamura, 2008).

Being 3D printed, HapKid can also prove to be a valuable resource for the open source and developer community whereby the developer can modify the device to make it look more aesthetically pleasing to children.

2.3 Electrical Design

HapKid is an impedance type of a haptic device whereby it senses the position of the operator in contact with the device and applies a force onto the operator according to the computed behaviour of the simulated surface or object. Robots designed for haptic rendering must possess low parasitic properties such as friction, inertia, control loop delay and must be back-drivable so as to provide the user with a flawless and transparent haptic experience.

Since HapKid primarily senses position and consequently provides a force, a position sensor and actuator form integral parts of its electrical design. These are complemented with a microcontroller and a compact driver circuitry for providing appropriate force-feedback to the user. For use in haptic applications, the actuator (typically a DC motor) must have features like low inertia, low friction, low backlash, low torque ripple and high torque output (Hannaford & Okamura, 2008). High transmission ratio should be avoided as they introduce significant amounts of friction which harms the fidelity of the haptic loop. Similarly, position sensors must also be low friction and possess a high resolution in addition to being linear in operation. These constraints require haptic devices to make high demands on actuator performance.

HapKid uses two 12V Rhino DC servo motors with planetary high precision encoders. Each of the encoders coupled with the DC motors are quad encoders which provide 28724 counts per revolution (CPR) each, enabling a 0.012° resolution. HapKid uses Arduino Mega 2560 as its microcontroller owing to its open source nature and simplicity in coding. The microcontroller performs sampling, processing of position data and simultaneously transfers the position data to the virtual environment and calculates force and torque at the desired position.

2.4 Interface Design

Interfacing refers to steps taken towards establishing a bi-directional communication between controller and PC. This is an integral part of haptic rendering whereby computation of forces takes place upon contact with virtual objects based on the position of the operator. In the physical world, the act of tapping a pencil on a table-top and feeling a slight force on the fingers is instantaneous. This is because human fingers possess tactile receptors that respond to frequencies of up to 10KHz. However, rendering with such high fidelity is neither a requirement nor an achievable goal of haptic interactions. Therefore, most haptic simulations operate at a control loop frequency of the order of 1 KHz. (Hannaford & Okamura, 2008). Such high frequency data transfer enables an appropriate visual representation of the virtual environment.

The algorithm starts by reading sensor values using quad encoding to increase the resolution. These sensor values (position and velocity measurements) are then converted from Joint space into Cartesian space. Next, the algorithm determines whether the user has collided with an object in the virtual environment or not. In case, it has, then force computation takes place as defined in the algorithm. This computed force is then transformed into the torque command provided to the actuators. In this manner, the haptic loop is completed as the user feels the force transmitted by the actuators with respect to his/her place inside the virtual environment.

3. Rehabilitation Using Virtual Environments

One of the most important features of robot-aided rehabilitation is the use of interactive virtual environments that can retain the interest of the patient for prolonged periods of time. This feature is most advantageous while developing rehabilitative devices for children as they find conventional therapy monotonous and often leave it mid-way. In this section, we present the various virtual environments rendered using HapKid.

3.1 Trajectory Tracing

In this virtual environment rendering, the child is faced with a predefined trajectory that must be traced using the HapKid end-effector. Any deviation from the desired path results in a slight reactionary force feedback felt at the end-effector. This is analogous to the initial stage of rehabilitation where the therapist draws a dotted trajectory of different strokes and gently holds the child's hand and guides him along. The child is allowed to deviate from the reference trajectory with a subdued reactionary force feedback which is governed by the equation below and can be varied by changing the damping constant B:

$$F = -B\,V \tag{5}$$

where F = Force

B = Damping constant

V = Velocity of the end effector

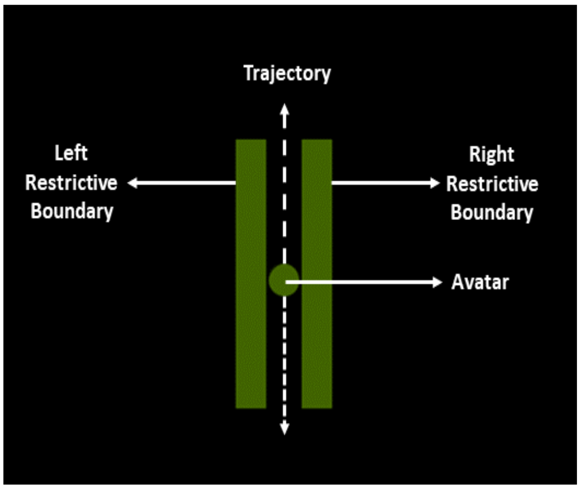

Figure 4. Image showing the dotted trajectory, avatar and the side boundaries whose force feedback is governed by Equation (5).

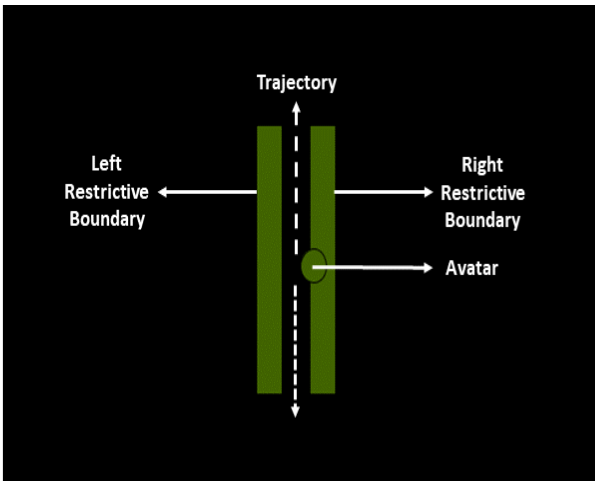

Figure 5. In this case, the device allows user to deviate from desired trajectory with some reactionary force feedback governed by Equation (5).

As the child makes progress in the rehabilitative/learning process, upon deviation from the reference trajectory a strong feedback force similar to that of a spring pushes him back on track. This force is governed by the Equation (6) and can be varied by changing the spring constant K:

$$F = -K\,X \tag{6}$$

where F = Force

K = constant

X = Distance

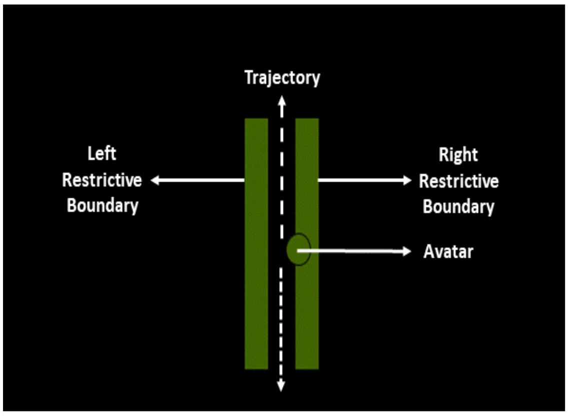

Figure 6. Image showing the instant where child deviates from the desired trajectory; since the boundaries are modelled such that they act as springs, thereby guiding the child back on trajectory.

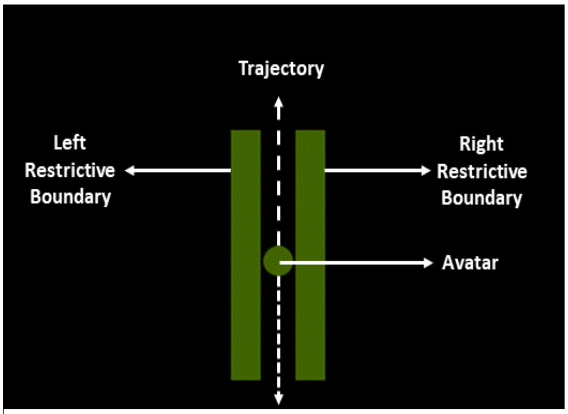

Figure 7. Image showing the instant after deviation, here the user has been guided to the desired trajectory. This is true for deviations from either side.

At the later stages of rehabilitative process, the trajectory tracing exercise is modified such that the feedback force given by the actuators on any slight deviation from the desired or the reference path is very strong leaving no scope for the user to make errors. This is realized by representing a very stiff wall in the virtual environment using Hooke's Law:

$$F = - K (X - X_w) \tag{7}$$

where F = force

K = stiffness constant

X = end-effectors position

X_w= wall location

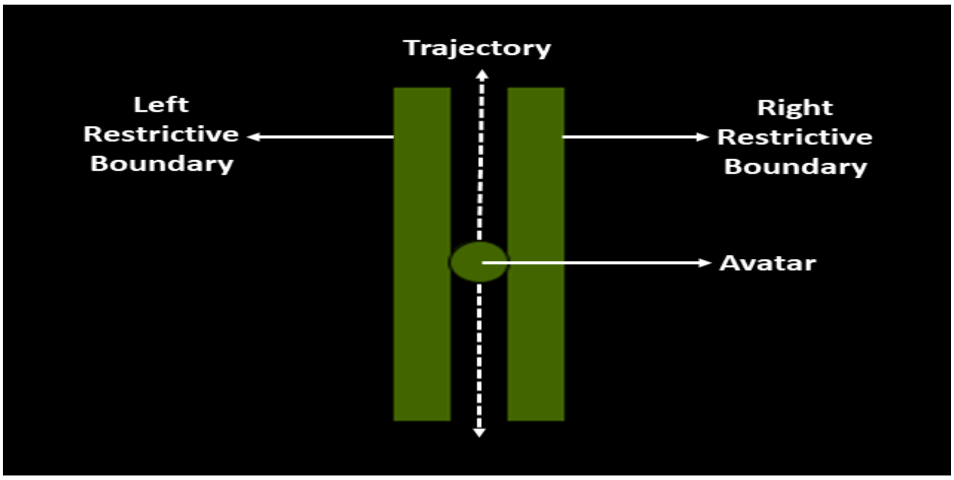

Figure 8. The force feedback is so strong that the side boundaries cannot allow avatar to pierce through, thus acting as stiff walls and do not allow child to deviate.

3.2 Pattern Following

In this environment, the child is made to follow a pattern with right angled turns having stiff haptic walls on either side. The feed-back force is strong enough to make the child stay within the desired pattern. After several trials, the force can be reduced so that the child learns to exert some amount of force by himself to stay within the desired region. This not only affects the user's muscle memory but also improves hand-eye coordination and most importantly forces him to exert some amount of force using the paretic limb. In all these rehabilitation exercises, the game-like nature keeps the child interested in therapy and the auditory feedback provides the required level of motivation.

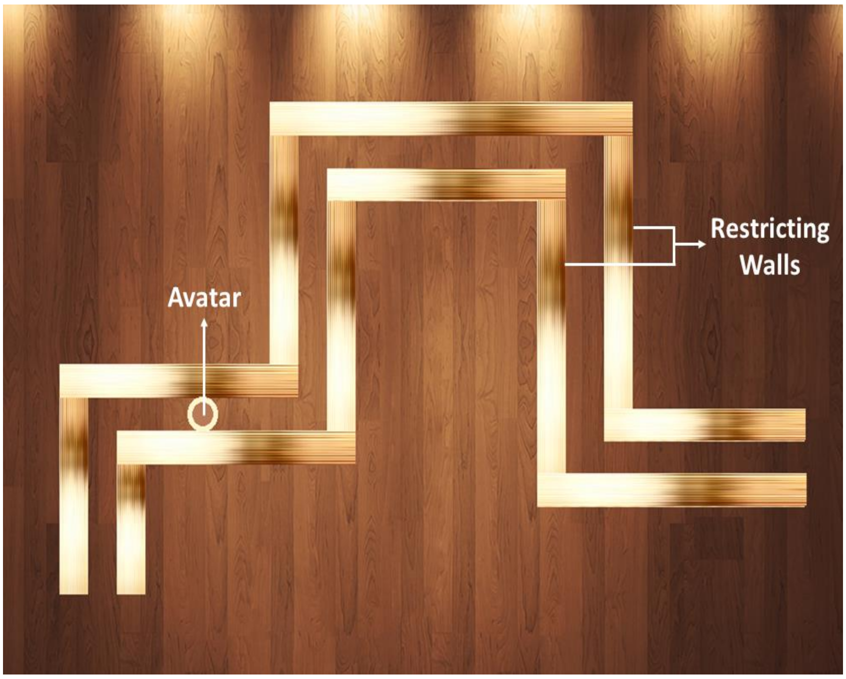

Figure 9. Immersive pattern-following rehabilitation exercise.

4. Discussion

In this paper, we presented the design and development of an affordable haptic device, the HapKid having a simple linkage structure for the rehabilitation of fine motor skills in children.

HapKid achieves this goal by guiding the child along a desired trajectory and applies kinesthetic assistive forces if the child deviates from desired path. It uses visual and auditory forms of force feedback during the rehabilitative exercises to retain the patient's interest and provide necessary motivation that aids in recovery. The device also helps in augmenting hand-eye coordination by including immersive pattern-following games.

Fabrication of mechanical parts with the help of technologies like 3D-Pinting and laser cutting makes the device customizable and cost effective. Use of open source hardware (Arduino Mega 2560) as the controller reduces its complexity. Also, the controller was programmed in an efficient manner resulting in higher achievable sampling frequency. To further reduce the cost of HapKid, we used simple DC motors with attached planetary gear system as actuators.

Testing of virtual environments with various force feedback models demonstrated the ability of HapKid to provide responsive, transparent and sufficient force feedback thereby allowing the user to practice trajectory tracking in a new and less-monotonous manner. The rendering of walls of varying stiffness allows the user to try exerting some force on his own using the paretic arm which is the ultimate aim of rehabilitation.

5. Limitations and Future Work

HapKid aims to revolutionize the way children suffering from motor deficits view rehabilitation by changing it from a monotonous, expensive activity to a game-like immersive experience. Since this is only an initial step towards contribution in this rapidly growing field, HapKid as a device does have some limitations. The device exhibits unstable behaviour beyond certain points in the workspace and would require an efficient control algorithm to achieve the necessary level of stability. In the future, our team would be interested in enhancing the design of HapKid such that it becomes aesthetically pleasing to children and use the device with children suffering from motor deficits.

6. Acknowledgements

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