On the Design of a Single Degree of Freedom Upper Arm Rehabilitation Robot with Its Gamification Methodology

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ABSTRACT

Throughout human life, neurological disorders may occur in body parts with accidents or other biological factors by destroying nerve commands. Stroke is one of the main causes among these disorders. Increase in stroke cases causes to increase requirement in continuous and efficient repetitive physiotherapy exercises that have great benefits in restoring functional losses by retraining motor movements. As a result, demand in treatments increases in parallel and it needs to be fulfilled in a simplest and fastest way. Given these facts, current study focuses on a simple low cost single degree of freedom tip follower rehabilitation system that focuses on forearm flexion/extension including supportive shoulder movements and that is implemented to a regular motion and interaction control structures with applications. With its simple mechanical structure, system provides a simple motion control for initial stages of treatment which is the patient passive mode, then follows an interaction control strategy with adjustable assistance and resistance, which is the patient active mode. Throughout the interaction control study, admittance control with variable coefficients have been carried out on the system for the patient active mode. At the end of the study, control algorithm variables created via case studies were implemented to the robotic rehabilitation system and functionality of the proposed approach was tested within designed game.

Keywords

Upper extremity rehabilitation, Interaction control, Game rehabilitation, Rehabilitation robotics.

1. INTRODUCTION

Neurological disorders that are caused by different reasons may affect life styles considering the fact that all humans are candidates for these syndromes. Stroke can be seen as one of the main causes of disability among people, where it has been reclassified as neurological disease by the World Health Organization (WHO), leaving its former classification as cardiovascular disease [1]. Increase in stroke cases and their survival rates after these events also introduce the requirement of neuro-rehabilitation procedures. In such conditions intensive repetitive motions should start immediately after the incident in order to create brain plasticity that has a huge effect in functional recovery [2]. As a result, demands of healthcare in rehabilitation increase gradually in population. On the other hand, number of professional medical personnel is not sufficient to meet the demand effectively [3]. Thus, researches in robotic rehabilitation gains popularity due to its advantages over classical rehabilitation in order to regain lost functions.

There exist many upper extremity rehabilitation systems that were already proposed in related literature [4-6] as this portion of the human body has considerable influence in daily lives of individuals. Thanks to related extremities high degrees of freedom, these rehabilitation systems get more complex in terms of their electromechanical structures, while trying to mimic desired motion as precise as possible. Unfortunately this fact not only affects the difficulty of their control algorithm, but also renders overall costs of the system to become so high.

As involving the robotized rehabilitation systems into the treatment processes, game based rehabilitation is also started to be developed so that participants can increase their motivation for recovery process without just focusing on treatments, instead, focusing on games that are actually prescription of the illness. It is also important that this kind of rehabilitation can provide the patient to experience the sense of achievement, even if she/he cannot achieve task in real world, by characterizing virtual environment and robotic system. The use of virtual reality and video games for rehabilitation increase motivation of the patients to perform the therapy tasks [7].

In light of this, current study focuses on a simple low cost single degree of freedom end effector type upper arm rehabilitation robot that helps to execute various upper arm movements such as forearm flexion/extension including supportive shoulder movements. Throughout the paper, a simple motion control and admittance control with proper force offset was introduced to execute regular rehabilitation procedures with patient passive and patient active [3] modes, respectively. In patient active mode, both robot assistance and resistance can be adjusted according to the situation of the patient. In order to decrease overall cost of the system, a low cost sensor was utilized on end effector for patient interaction. For enhancing its treatment capabilities by increasing cognitive effects, designed virtual game that aims to drive different motions were also implemented to the robotic system and case studies were carried on three different healthy people to verify proposed control structures performance.

2. REHABILITATION SYSTEM

Several types of different robotic systems are used as the rehabilitation robot. They can be complex exoskeleton systems or relatively less complex tip follower types of devices. In this work, in order to reduce the complexity and overall cost, simple tip follower type of end effector robot that aims to forearm flexion/extension including supportive shoulder movements is utilized with integrating game interface that is developed by our working group. The control strategies are embedded behind the developed game levels so that the forearm flexion/extension movement can be carried out repeatedly by the patient bearably with more entertainment.

The utilized system components basically consist of a force sensor placed in a link and a rotary actuator connected to link (Figure 1).

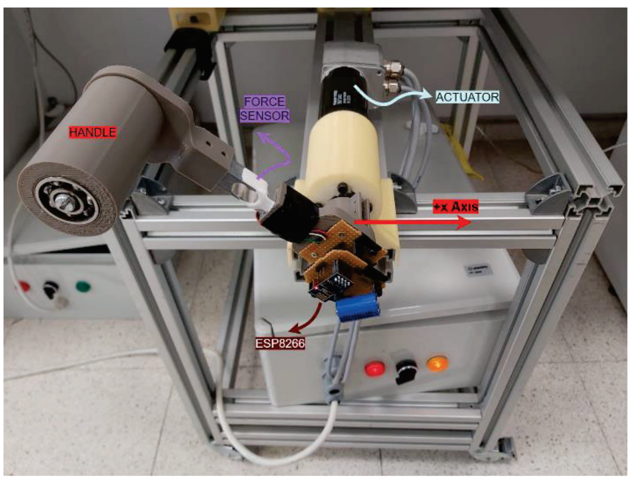

Figure 1. Rehabilitation system

The main reason of using a simple force sensor here, instead of using a rotary torque sensor, is to keep the overall cost reduced in the system. Besides, if a rotary torque sensor is placed in the rotation axis of the link, it is affected by both the actuator and force link directly and that can leads some problems [8]. The overall system can be treated as a simple pendulum, where its non-linear dynamic equation of motion is as in the Equation 1.

$$\tau(\theta, \omega, \alpha) = (ml)\alpha + c\omega + mgl\cos\theta \quad (1)$$

where τ is the required dynamic torque, *m* is the mass on the end effector of the system, *l* is the link length, *c* is the rotational damping coefficient, θ is the rotation angle with respect to defined *x*-axis in Figure 1, ω is rotational velocity of link and α is the rotational acceleration of link. Comparing to external dynamic affects, the rotational inertia becomes relatively small, therefore the acceleration terms can be omitted from the Equation 1.

Since the force sensor is placed in the link, during the action of continuous rotation, an entanglement of cable problem arises, which will cause the system unable to work. This problem can be solved by using a slip ring, where the mechanical design is problematic with the losses in transferring motion. Another solution is to use a microcontroller that rotates together with the link and eventually interpret and transmit the sensor data wirelessly to the main controller. The second solution is decided to be utilized in the system.

In this work, wireless transmission is utilized by using a cost effective ESP8266 Wi-Fi module that is preferred frequently in the market [9], where it is a reliable data link protocol in terms of hardware and software. Since the control strategy of the system is very crucial for the application, the main PC that drives the control algorithm should receive the data in real time from the sensor, thus the data transmission rate of the wireless system must be as high as possible. In order to achieve this, User Datagram Protocol (UDP) is chosen as the data transfer protocol in the transport layer, due to the fact that it is relatively fast over other protocols.

Latency arises as a new problem when involving wireless data transmission into the action. Therefore, latency is firstly measured and interpreted as if it is possible to compensate. In order to determine the performance of force intention measurements from the user via wireless force sensor, additional tethered measurement device is implemented to the system, which gives eventually the opportunity to compare both tethered and wireless data communication. As the measurement device, torque sensor (FUTEK TRS300) is utilized only for the comparison. The system with wireless force sensor design and torque sensor measure the identical force input at the same time (Figure 2) and data are collected with a common model that is constructed in Simulink environment.

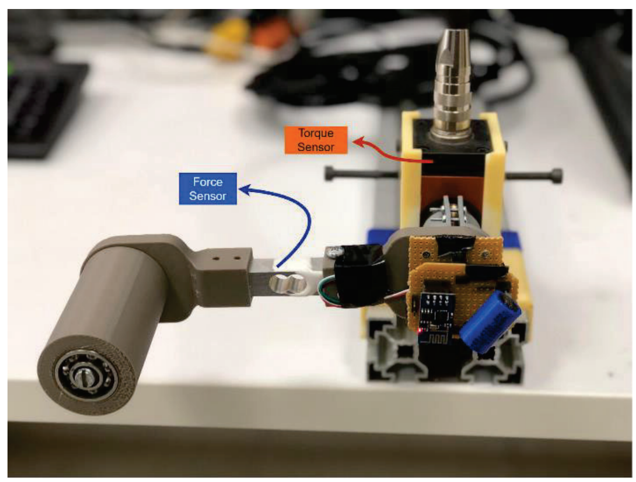

Figure 2. Fixed system with torque sensor

Analog torque sensor data is interpreted by the Humusoft MF624 data acquisition card directly, where the data coming via UDP is interpreted with Simulink's real time UDP reading block. As seen in Figure 3, the data is plotted in the common time-based graph and determined that the latency is approximately 250 milliseconds.

As the actuator, a Maxon brushless DC motor (250 W, 5000 rpm, 331 mNm) is used together with its EPOS2 driver system. Utilizing EPOS2 communication command libraries from Eugenio [10], the system is driven real time with Simulink, thus all control algorithms are simply applied in Simulink environment. In applying motion control, this command libraries are utilized and the performance of this type of control becomes dependent on the Maxon's auto-tune parameters.

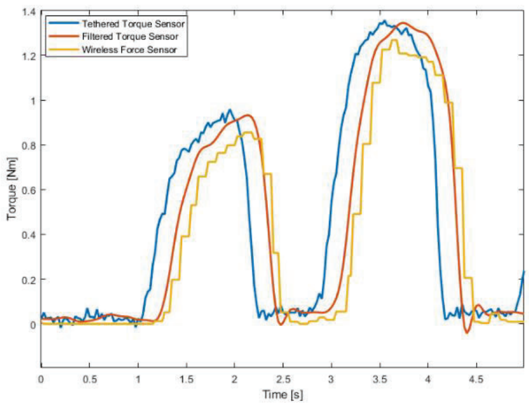

Figure 3. Latency test in common model

To date, commanding Maxon Motors from MATLAB and Simulink via EPOS2 driver system is developed from Eugenio at file exchange center of MATLAB. This is very useful for developers that desire to use MATLAB as a main platform of commanding. Developed files are based on libraries that are published from Maxon,Inc.

3. INTERACTION CONTROL STRATEGIES

In rehabilitation systems that deals with neurologic disorders, interaction with patients is important and needs to be carried out carefully. With these interactions, the patients are directly involved to therapy sessions. For this kind of interaction, different types of control strategies are developed with including direct and indirect type of force controls. By considering the non-back-drivability of our system, in this work admittance control strategy is carried out. It introduces a dynamic behavior between applied force/torque and motion and its dynamic can be written in Laplace domain as in Equation 2.

$$A(s) = \frac{\omega(s)}{\tau(s)} = \frac{s}{J_v s^2 + b_v s + \kappa_v} \qquad (2)$$

where $A(s)$ is the virtual admittance, J_v is the virtual rotational inertia, b_v is the virtual rotational damping coefficient, κ_v is the virtual rotational spring constant.

Utilizing variable admittance gain has considerable advantages due to the fact that they are considered as the virtual dynamics. At the stable undisturbed position of the system where there exists small or no motion intention coming from the user, selected virtual admittance coefficients should be high enough to keep stability. If user tries to move the system, by adapting the virtual admittance coefficients to desired manner according to need of assistance or resistance has advantages in considering the rehabilitation type. For instance, decreasing the admittance virtual coefficients as the force intention from user increases, the motion becomes easier to achieve, which is suitable for assistance mode. This adaptation can be utilized by using the data from the patient and combining with the gaming interface.

Additionally, offset force is applied according to assistance or resistance needed, which is determined in the difficulty levels of the games under rehabilitation requirements.

4. REHABILITATION PROCEDURES

In robotic rehabilitation, different operation modes of device is needed in order to be adjusted to different patients, who needs different dosage or intensity of treatment. These operation modes in treatment strongly depend on the patient situation. These modes can simply be generalized as patient passive, patient active with assistance and patient active with resistance. In patient active modes, the need of interaction control becomes a must, where the force sensor is activated.

4.1 Patient Passive Mode

In patient passive treatments, patients do not perform dedicated treatment activity due to the neurological disorder. Instead, the overall motion is carried out solely by the robotic system in order to form plasticity in the brain. In early stages of rehabilitation, this treatment methodology plays a vital role in patient recovery, due to the fact that it allows regaining lost motor functions via plasticity.

In gamification process, the first difficulty levels are filled with this kind of treatment methodology by assuming the plasticity is not created in the early stages. Due to the fact that the actuator of the rehabilitation system is driven without waiting for any motion intention from the patient, a simple rotational velocity control can be applied to the system as the control strategy with a predefined reference velocity profile.

4.2 Patient Active Mode

It is obvious that patients can only participate the active treatments, if they regain some amount of strength and ability to send neurological signals to the affected extremities. In patient active mode treatments, patients must provide some level of muscle activity to perform related procedures where the system is activated, then this intention is amplified by the control algorithm in order to drive actuator of the rehabilitation system.

The activeness in the treatment process is achieved by using the commands that comes from the patient with force sensor. The

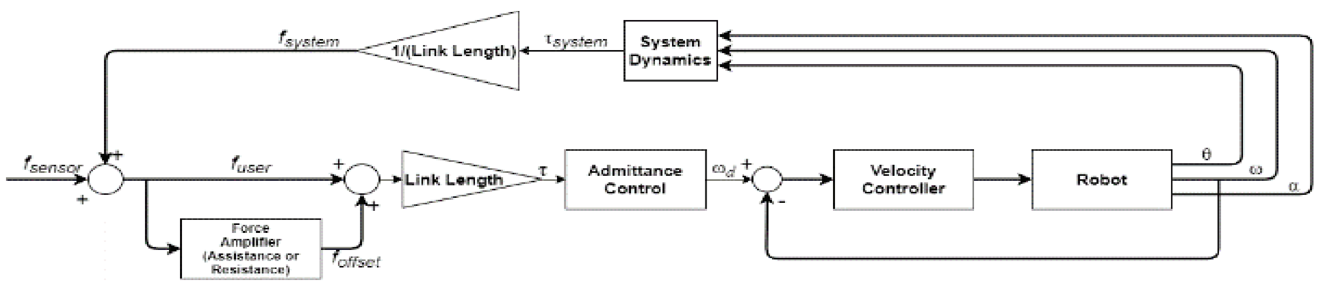

Figure 4. Admittance control block diagram

admittance control scheme is applied as the outer and inner loop together as seen in Figure 4.

In Figure 4, f_{offset} represents predefined offset force on the system and f_{sensor} represents the measured force by the sensor that comes from the user and system dynamics. Admittance control block accepts torque error that was created from the force error and determines desired rotational velocity of application shaft, ω_d. According to rotational velocity reference value, inner velocity control is executed and dynamic motion creates system torque, represented by τ_{system}.

Force amplifier block creates offset force (f_{offset}) that is related with rehabilitation mode (assistive or resistive) and it has a saturation value. If the procedure is assistive, it is determined with the Equation 3.

$$f_{offset} = \begin{cases} f_{user}, & f_{user} < f_{saturation} \\ f_{saturation}, & f_{user} \geq f_{saturation} \end{cases} \quad (3)$$

If the procedure is resistive, then it is determined with the Equation 4.

$$f_{offset} = \begin{cases} -f_{user}, & f_{user} < f_{saturation} \\ -f_{saturation}, & f_{user} \geq f_{saturation} \end{cases} \quad (4)$$

It works together or against user that increase or decrease effort by changing torque error that is applied to admittance control block. Together with virtual dynamics of admittance control, it strongly affects the tendency of rehabilitation procedure. However, when no intention comes from user (f_{user}=0), offset force should be zero as well, since it must not affect the torque error, which is possible with the modeled equations. In resistive case, the movement does not start until the $f_{saturation}$ is reached by the user, which affects the user effort dramatically.

4.2.1 Patient Active with Assistance

In early stages of the treatment process, after creating plasticity, patient should be involved to treatment directly. Since it is not fully possible to utilize the movement solely, some help is needed. In such cases, the assistance is carried out by the control algorithm, where the overall motion is carried out in such a way that patients should feel as if the system is driven by them. The assistance level is determined by the patient intention, eventually value of f_{offset} and admittance coefficients are applied.

4.2.2 Patient Active with Resistance

After participating to active treatments with assistance, it is needed for patients to have a resistive motion in order to gain muscle and control movements under resistance properly. For this reason, resistance is included to the same control algorithm, where the f_{offset} and virtual admittance gains are affected again. Here, it is obvious that the f_{offset} should be negative value in order to activate a negative offset force to the patient. Also, it is seen that if the admittance virtual coefficients are kept higher, it also results in some resistance to the user.

5. GAMING INTERFACE

Treatment process of neurological disorders is relatively boring for patients who should do exercises repeatedly and intensively with exhausting help of physiotherapists. As literature supports, gamification for this purpose gives a remarkable results in increasing participations with enthusiasm and increased cognitive effects. With the given facts, in this work, one virtual game that suit the considered robotic application is developed to implement the motions to virtual environment in which the movements utilized by the user gets harder as the dedicated game levels increase.

In this work, game-rehabilitation is applied via creating a virtual environment on Unity3D and communicating this tool with rehabilitation control model that was built with Simulink. Unity is a powerful and popular 3D game engine developed by Unity Technologies, which is first released in 2005 [11]. Primary game concepts are based on functionality, therefore visual effects inside the game and other design concepts such as graphical user interface and flow on the game is not primarily concerned and instead, their developments are left for future works.

Catching an airplane game is developed with respect to concerning rehabilitation modes; patient passive mode, patient active with assistive and resistive.

5.1 Catching an Airplane Game

The main concept behind the developed game is the fact that user tries to rotate a swatter in order to catch an airplane that files on a constrained circular motion (Figure 5).

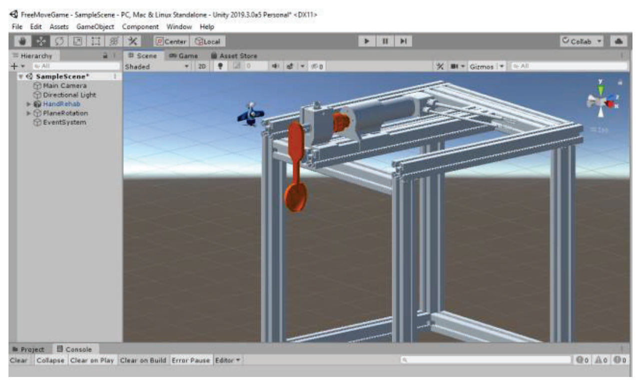

Figure 5. Catching an airplane game scene in Unity3D

Since there is no reference point that all the movements are related and eventually the movement is utilized in continuous motion, the virtual spring coefficient is omitted from the admittance control algorithm ($\kappa_v = 0$) in order to have a free movement in the constrained circular motion path. In difficulty levels where the patient is active, the interaction control is included and the flying velocity of the virtual airplane is bind to the velocity of the user, which is the velocity of the scatter. Therefore, in order to catch the airplane, user should move robot link as fast as she/he can. If the

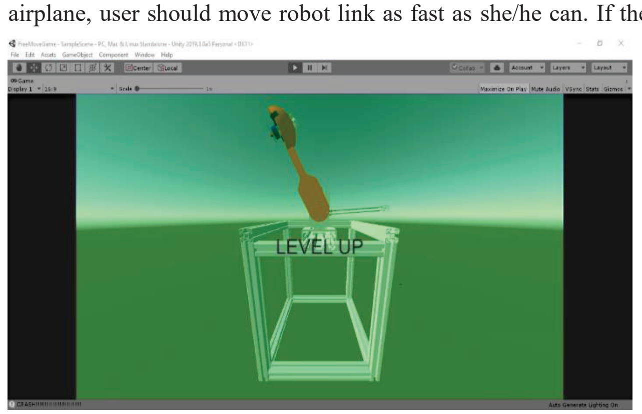

Figure 6. Catching an airplane game level achieved scene in Unity3D

motion is interrupted and stopped by the user for some reason, virtual airplane flies with a predefined minimum velocity, where eventually the airplane is crashed to scatter behind it, which means that the level is failed. Once the airplane is caught with the scatter in the rotating direction, dedicated level is counted as achieved (Figure 6).

The virtual admittance parameters are created as dependent on the force intention that comes from the user due to the fact that after reaching some level of velocity, the virtual damping coefficient becomes dominant and relatively big counter force is acted on user. In order to avoid this fact, the virtual coefficient multiplier is created as in the graph Figure 7, where the stability is kept in undisturbed initial condition. After some distribution force is applied from the user, the coefficients shrinks until the half of their default values.

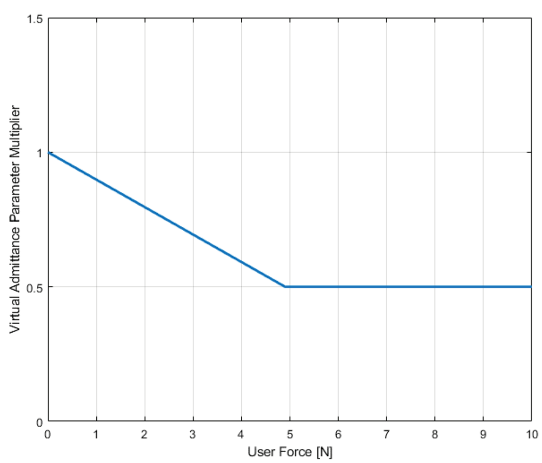

Figure 7. Virtual admittance parameter multiplier with respect to user force

Levels of the game are shaped with rehabilitation modes. First, the system aims to create plasticity in the brain, where it is a patient-passive motions. Here, the control structure is constructed basically with a velocity controller, where there is no need to interaction with the user. Then, the levels with patient-active modes are faced. In such levels, the saturation force, virtual admittance coefficients and airplane flying velocity dependency defines the difficulty of the levels. These coefficients are determined by trials, however it is better to need a deeper investigations that are left as future work. Saturation forces are applied in defining offset forces as mentioned in previous section with Equation 3 and Equation 4. In the active assistance cases, the user force is doubled until $f_{saturation}$ is reached, in which assistive force is very dominant. If the $f_{saturation}$ is zero, then the motion is directly affected by the virtual admittance coefficients. In the active resistance cases, in order to begin the movement, user should apply a force bigger than $f_{saturation}$.

With the needs of treatment processes, game with 17 levels are designed and tabulated in Table 1.

Table 1. Catching an airplane game difficulty level parameters

Level	Control Mode	Control Reference	Admittance Control Default Parameters	Airplane Default Velocity
L1	Passive Mode	ω_{ref} = 15rpm	J_v=0, b_v=0	ω_{plane} = 5rpm
L2	Passive Mode	ω_{ref} = 10rpm	J_v=0, b_v=0	ω_{plane} = 5rpm
L3	Active Assist Mode	$f_{saturation}$= 30N	J_v=0.1, b_v=0.1	ω_{plane} = $0.5\omega_{system}$
L4	Active Assist Mode	$f_{saturation}$= 30N	J_v=0.1, b_v=0.1	ω_{plane} = $0.8\omega_{system}$
L5	Active Assist Mode	$f_{saturation}$= 30N	J_v=0.1, b_v=0.25	ω_{plane} = $0.5\omega_{system}$
L6	Active Assist Mode	$f_{saturation}$= 30N	J_v=0.1, b_v=0.25	ω_{plane} = $0.8\omega_{system}$
L7	Active Assist Mode	$f_{saturation}$= 15N	J_v=0.1, b_v=0.1	ω_{plane} = $0.5\omega_{system}$
L8	Active Assist Mode	$f_{saturation}$= 15N	J_v=0.1, b_v=0.1	ω_{plane} = $0.8\omega_{system}$
L9	Active Assist Mode	$f_{saturation}$= 15N	J_v=0.1, b_v=0.25	ω_{plane} = $0.5\omega_{system}$
L10	Active Assist Mode	$f_{saturation}$= 15N	J_v=0.1, b_v=0.25	ω_{plane} = $0.8\omega_{system}$
L11	Active Mode	$f_{saturation}$= 0N	J_v=0.1, b_v=0.1	ω_{plane} = $0.5\omega_{system}$
L12	Active Mode	$f_{saturation}$= 0N	J_v=0.1, b_v=0.1	ω_{plane} = $0.8\omega_{system}$
L13	Active Mode	$f_{saturation}$= 0N	J_v=0.1, b_v=0.25	ω_{plane} = $0.5\omega_{system}$
L14	Active Mode	$f_{saturation}$= 0N	J_v=0.1, b_v=0.25	ω_{plane} = $0.8\omega_{system}$
L15	Active Resist Mode	$f_{saturation}$= 10N	J_v=0.1, b_v=0.1	ω_{plane} = $0.5\omega_{system}$
L16	Active Resist Mode	$f_{saturation}$= 15N	J_v=0.1, b_v=0.1	ω_{plane} = $0.5\omega_{system}$
L17	Active Resist Mode	$f_{saturation}$= 20N	J_v=0.1, b_v=0.1	ω_{plane} = $0.5\omega_{system}$

Three healthy people (*A,B,C*) played this rehabilitation game with the setup and the results are tabulated as in Table 2. In this game, the initial position of the scatter is 90° with respect to defined *x*-axis and the airplane is initially placed in coincident with +*x* axis, which means that airplane is 90° behind due to the fact that the overall motion is directed in counter-clockwise.

Table 2. Catching an airplane game results in each level

		Average Velocity [rpm]	Average User Force [N]	Rotation [°]	Estimated Energy [N rad]	Duration [s]
L1	*A*	15.00	0.00	405	0.00	4.50
	B	15.00	0.00	405	0.00	4.50
	C	15.00	0.00	405	0.00	4.50
L2	*A*	10.00	0.00	540	0.00	9.00
	B	10.00	0.00	540	0.00	9.00
	C	10.00	0.00	540	0.00	9.00
L3	*A*	26.89	6.04	723	76.23	4.53
	B	33.10	8.36	654	95.46	3.48
	C	30.07	7.33	695	88.87	4.00
L4	*A*	44.37	8.19	1886	269.82	7.45
	B	44.94	9.41	1610	264.42	6.10
	C	40.25	7.99	1805	251.65	7.75
L5	*A*	23.04	10.66	788	146.60	5.80
	B	31.80	15.10	691	182.17	3.80
	C	42.55	20.84	983	357.65	4.08
L6	*A*	39.09	17.89	1770	552.53	7.80
	B	38.88	17.23	1826	549.07	8.13
	C	40.09	17.78	2035	631.70	8.90
L7	*A*	32.20	7.38	625	80.61	3.43
	B	44.64	11.30	616	121.44	2.40
	C	44.72	14.48	619	156.49	2.43
L8	*A*	50.94	10.48	1568	286.83	5.45
	B	50.83	10.75	1552	291.23	5.40
	C	49.23	11.06	1601	309.07	5.75
L9	*A*	28.31	13.63	736	175.23	4.43
	B	32.67	16.27	689	195.91	3.60
	C	31.64	15.97	1040	289.99	5.70
L10	*A*	32.90	16.03	2091	584.99	10.95
	B	37.15	18.79	1991	653.07	9.28
	C	42.32	23.62	1703	701.87	7.10
L11	*A*	29.60	13.57	689	163.15	4.05
	B	35.16	15.92	678	188.41	3.30
	C	40.94	20.11	653	229.46	2.78
L12	*A*	39.42	15.69	1803	493.91	7.90
	B	42.01	14.88	2016	523.57	8.28
	C	44.36	18.31	1575	503.48	6.20
L13	*A*	19.45	17.75	873	270.68	7.60
	B	25.13	22.72	784	310.89	5.35
	C	27.11	26.61	715	331.93	4.40
L14	*A*	27.45	24.34	2767	1175.30	17.23
	B	29.03	25.80	2559	1152.40	15.18
	C	22.98	20.18	3691	1299.70	27.50
L15	*A*	23.29	17.99	796	250.06	5.73
	B	16.19	16.10	1039	292.12	10.93
	C	22.79	19.34	787	265.79	5.85
L16	*A*	25.39	22.47	744	291.64	5.05
	B	18.78	22.37	925	361.01	8.30
	C	20.08	23.21	849	343.78	7.20
L17	*A*	19.81	25.18	859	377.33	7.30
	B	18.47	26.88	911	427.54	8.40
	C	18.72	27.06	887	419.01	8.10

According to tabulated results, user increases her/his effort due to the changes in control algorithm and difficulty parameters. There is an undeniable correlation between the admittance coefficients and the applied force as well as spending energy. For example, by keeping the offset force and the airplane velocity ratio unchanged, the effect of the admittance control coefficients can be verified in level 3 and level 5 or level 4 and level 6. Offset force affects the overall energy and intention force less, but still can be very useful in the applied algorithms, especially its initial help to move the system is important for active assistance cases. Also, in resistance cases, user must apply more force to initiate the motion, together with the effect of admittance dynamics. The most energy drained levels are the ones in that velocity ratio of the airplane is high due to the fact that it is harder to catch the airplane with the scatter and naturally it takes time to be caught.

6. CONCLUSION

This study mainly introduces a proof of concept and application of controller in action on a proposed cost effective rehabilitation system with combining gaming interface. In the system, sensor data is interpreted and transferred wirelessly in local without problem. This data transmission is achieved via UDP and in the receiving side, system control model that is constructed with Simulink is combined to game engine Unity 3D. After the latency test, the additional relatively expensive torque sensor is removed from the system and the system is composed of one motor, motor driver, simple force sensor, force sensor operational amplifier, wireless module and necessary power suppliers. Although in the system relatively expensive motor was used, it can be replaced with a regular DC motor. In this case, the motion control should also be implemented in the system, along with the decrease in cost.

When the data of people playing the game are examined, the energy consumed varies according to the levels and generally increases gradually. This makes it possible to record the data numerically and observe the healing objectively. At the end of the study, we can conclude that the system is produced inexpensively, and promising results were acquired, where gamification works without an issue.

In this work, the gaming levels are predefined fixed and does not support the implementation of assistance-as-needed paradigm, therefore the slacking for some patients can come up. Working on assistance-as-needed algorithms will be implemented in the gamification algorithms as future works and with the implementation of stable game flows, the clinical trials can be utilized hereafter.

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