Upper Limp Movement Analysis of Patients with Neuromuscular Disorders Using Data from a Novel Rehabilitation Gaming Platform

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Abstract. This paper describes the methodology for analyzing data from a novel platform that utilizes gamification techniques targeting patients with neuromuscular disorders that result in upper-limb movement limitations. The patient is asked to perform a number of sessions as prescribed by the physician for rehabilitation purposes, while the data are used to assess their progress. The hand movement is analyzed, and features are extracted regarding the movement patterns velocity, jitter, and trajectory. A set of sessions derived from healthy individuals have being recorded and analyzed so as to establish a baseline for the metrics. A statistical analysis of the differences between the healthy subjects and the patients is performed, helping us to focus on features of interest to the disease. The results will help determine how the patients are improving their motor skills as the therapy progress, and accordingly adjust the number and type of sessions prescribed in a personalised manner.

Keywords: Serious Game, Rehabilitation, Signal-Analysis

1 Introduction

Motor control is considered one of the most difficult set of functionalities of the human body. It is a process or a set of sub-processes, during which humans move and coordinate their muscles and limbs so they can perform a motor skill. Every human from the moment of his birth trains in motor control (Motor Learning) through the integration of sensory-motor information. In Motor Learning, movements are consolidated in the Central Nervous System (CNS), at first through observation and then by repeatedly performing them. In some cases, certain pathologies affect the CNS, resulting in the loss of cognitive functions of the brain. This may impact several motor functions and cause partial or complete loss of them. Rehabilitation programs aim to detect any motor deficits of each patient and help them regain control of their movements through motor learning. The standard method of doing that, is the repetition of a movement's correct form, so that it can be permanently stored in the CNS. The repetitive training of isolated movements is a fundamental principle behind improving the outcome of motor rehabilitation.

Over the recent years, there has been an increasing interest on how technology can assist physical rehabilitation and conventional treatment methods for patients with physical impairments [1] [2]. With recent advancements in technology, a new domain, that combines exergames, gamification mechanisms and traditional rehabilitation methodologies, has emerged [3]. Therapeutic solutions, that combine novel software and hardware components, are implemented to facilitate the rehabilitation for patients with motor deficits. They can facilitate the process of Motor Learning, by offering the ability of executing a series of repetitive and functional movements efficiently [4], in a less monotonous way.

A rehabilitation platform that can be used as a tool for the medical treatment of patients with upper extremity motion difficulties is presented on this paper. The proposed platform was not created with a specific pathological condition in mind and its objective is physical impairments of the upper limbs, regardless of the cause.

The platform will be used to determine concepts and methods that will increment the efficacy of the Motor Learning process. Specifically, the form and the frequency of repetitions that a movement should be performed will be examined, with the purpose of optimizing therapeutic programs.

The main focus of the paper is the analysis of the data gathered during rehabilitation sessions. Certain features are extracted and compared across a sample of patients and healthy subjects, and evaluated as indicators of improvement.

2 Description of Milord

The therapy program conducted within the implementation idea presented above, aims at the rehabilitation of the arms and focuses on the following exercise movements: flexion/extension of the shoulder, horizontal adduction/abduction of the shoulder, and supination/pronation of the forearm. The repetition of these specific movements as many times as possible is the primary goal. In its current state, the platform has one game scenario that the user can perform these rehabilitation exercises in (term "user" refers to a candidate patient, a medical professional or an individual that is testing the game). The scenario follows the flying simulation paradigm. Inside the virtual world of the game, the user controls a red polygonish airplane. The interaction between the user and this game object (avatar) is achieved by the camera tracker Leap Motion Controller [https://www.leapmotion.com], which uses computer vision technology to recognize hands in the scene and calculates a set of measurements that describe them. The user places his hand above the sensor, and can move it along the horizontal and vertical plane, as also rotate it along the depth axis. Inside the virtual world of the game, the airplane mimics the hand's movement. This amplifies the sense of immersion of the user in the game world by reinforcing the game metaphor - the impression that the hand is the airplane. The purpose of the game is for the user to guide the avatar through orthogonal objects (gates) that head towards it.

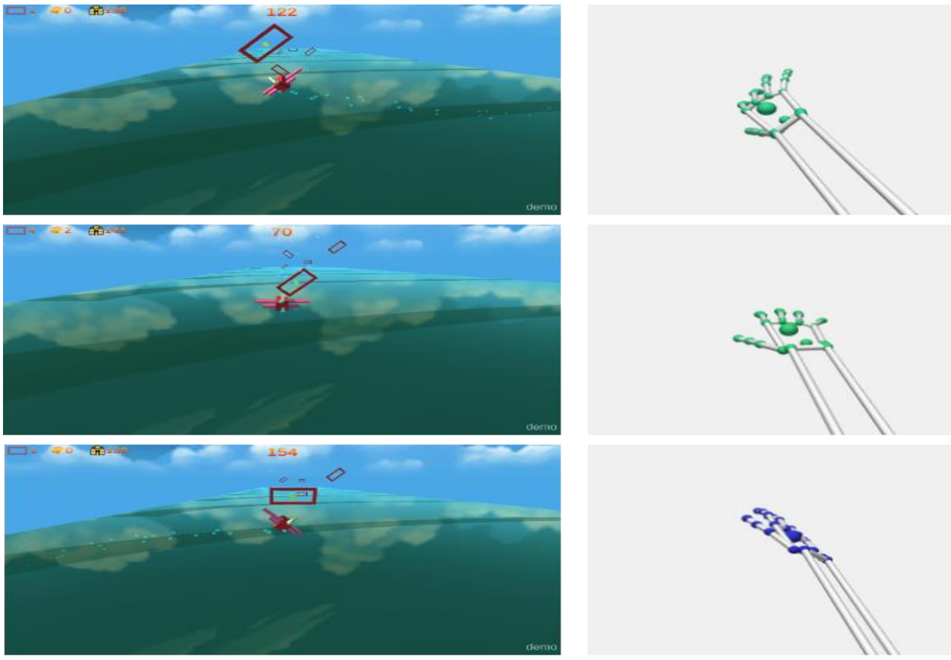

Fig. 1. Movement of the hand and its effect on the virtual world of the game

The goal is the highest possible number of repetitions, so the condition for the end of a game session is either a time limit or a limit on the number of the gates that the user will successfully guide the airplane through (successful gates). Either of these limits is set by the supervising physician depending on the patient’s rehabilitation needs and his fatigue from muscle strain. Because of the closely defined set of movement exercises, it was a requirement based design decision that the airplane avatar of the game -and by extension the hand in the real world - cannot move with six degrees of freedom (DOF) [5]. Thus the airplane's movement is restricted to the X and Y plane. The illusion that the airplane advances forward is given by making every game object in the scene move towards the player's avatar. The movement across the horizontal and vertical plane corresponds to these pairs of movement: flexion/extension and adduction/abduction. Pronation and supination of the arm is mapped to the rotation of the airplane on Z axis.

The gate objects that the user has to lead the aircraft in, appears in a predefined 3x3 grid - meaning there are 9 possible places where gates can appear in the screen (**Fig. 2**). They were arranged in this manner to reinforce the consistency of the data that are recorded during therapy sessions and respectively to make the analysis process more reliable. This will assist in reaching conclusions about the patterns of the hand's movement and improve the rehabilitation regimen, without adding other influencing factors. The order of display of the gates is random, and is handled by a pseudo-random algorithm, with a modification introduced in it, that ensures each gate will emerge at least once in a game session, given that the overall number of gates will be $N \geq 9$. The randomness is an important factor in this rehabilitation scenario, because it averts the patient from memorizing the order in which the gates appear on the screen, and from completing a game session by memory. Therefore, the results we obtain from the analysis are unbiased in this respect. This is also true for the process of assessment of the patient's functional status, which usually happens initially when the patient joins the rehabilitation program and when she finally completes it. In such a case, the exercise scenario should be identical both for the initial and the final assessment, for the results to be comparable. This assessment case was taken into account during the development and, the option for a physician to be able to choose a previous played scenario was incorporated.

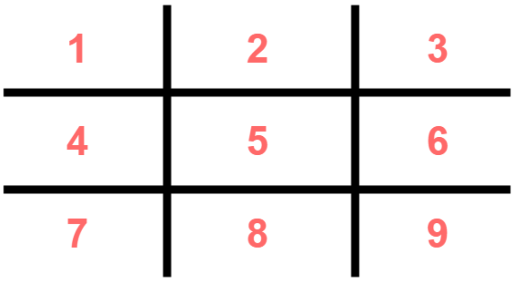

Fig. 2. Gates 3x3 grid where the gates appear

3 Analysis Methodology

The main focus of the analysis on the current stage is to determine the variables that are going to be examined and explore the differences between healthy subjects and patients.

The frame rate is capped at 60 fps but minor differences in the time that the frames appear may occur. Since the data collection rate is based on the game frame rate, in order to facilitate an analysis that support exploration in the frequency domain the time-series of the coordinates are interpolated at a steady rate of 16.667 milliseconds.

During the gameplay there are two states, the user is either moving the hand or user tries to keep it steady. For the analysis we divide the gameplay sessions into parts. Each part corresponds to the period of each time window (W_i), between two consecutive gates. Since the gates (G_i) are moving towards the avatar in controlled pace these time windows all have the same duration, with the exception of the first gate which appears a few seconds after the start in order to provide the user ample time to get accustomed to the game.

On each part (W_i) we can distinct 3 different sub-periods.

1. Response (DT1: t0-t1): it refers to the period of time after the user has reached the Gi gate and when they become aware of the upcoming gate Gi+1 and they begin to move towards it. Steady period.
2. Movement (DT2: t1-t2): it refers to the period of time where the user is moving from Gi towards the upcoming gate G_{i+1}. Movement period.
3. Stabilize (DT3: t2-t3): it refers to the period of time after the user has arrived to the X, Y coordinates that correspond to the G_{i+1} gate and is waiting to reach it (plane pass through the gate). Steady period.

The time points t_{i0}, t_{i1}, t_{i2}, t_{i3} are defined as follow

- t0: the time point when the avatar collided with the previous gate or had the same Z in case the user missed it.
- t1: the time point after the user has passed through the previous gate and started moving towards the upcoming gate
- t2: the time point when the user considers that has reached the upcoming gate and greatly reduces the movement
- t3: the time point when the avatar collided with the upcoming gate or had the same Z in case the user missed it.

Regarding the t0 and t3 time points, $t_{i-1,3}$ is equal to t_{i0}. For the first target t_1 is defined as the start of the session t_{10}=0. These time points are registered in the raw data that are produced during the gaming session. Time points t1 and t2 on the other hand are calculated based on the movement pattern analysis.

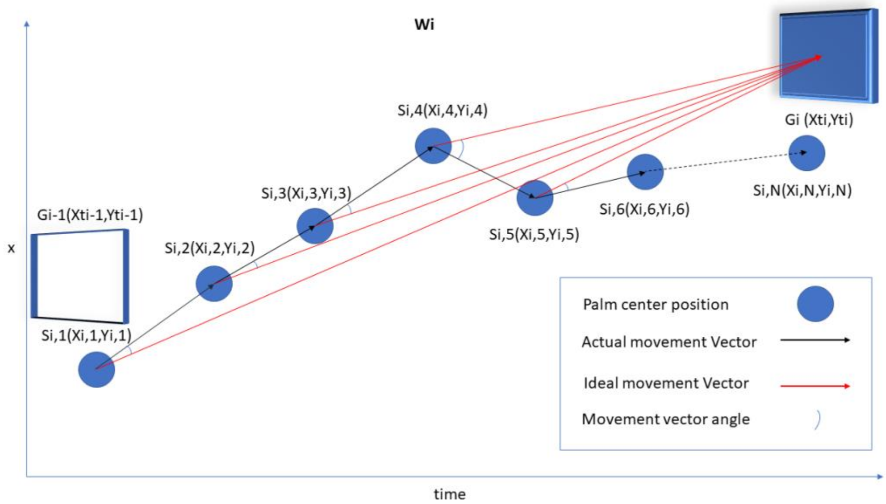

Fig. 3. Movement from gate G_{i-1} to G_i . The $S_{i,j}$ represents the hand position on each j frame for every i window (W_i).

Fig. 3 depicts the movement from gate G_{i-1} to $G_{i,}$

The t1 time point is determined as followed:

1. Determine the periods when the hand is moving
   a. Calculate the instantaneous velocity $V_{i,j}$ (the velocity on j frame of window W_i).
   b. Calculate the rolling average (length =15) of the instantaneous velocity.
   c. Calculate the distribution of the instantaneous velocities of window W_i.
   d. The hand is considered to be moving the rolling average is above the 75^{th} percentile of the instantaneous velocity
2. Determine when the hand is moving towards the upcoming target G_i
   a. Calculate the Euclidean vector $S_{i,j}$ of every two consecutively points (S_i1 to S_i2, S_i2 to S_i3 etc.)
   b. Compare each vector $S_{i,j}$ to the vector starting from $S_{i1}(X_{i1}, Y_{i1})$ to $G_{i1+1}(X_{i1+1}, Y_{i1+1})$ and extract the angle difference, $< S_i1G_{i1+1}$
   c. Calculate the circular angle on a rolling window.
   d. T1 is defined as the first data point where the circular angle difference was below a certain threshold (10^o) or the first time it was found to be below the 95^{th} percentile

The t2 time is described as the first time after the t1 time point when the movement has been halted or greatly reduced, while also being on X,Y coordinates close the Gi, in case the user successfully hit the target.

Currently the features examined involve the description of the movement in the time domain (velocity, acceleration, trajection, jitter, etc.)

- Durations of DT1/DT2/DT3: the durations in milliseconds
- Mean/SD Velocity DT1/DT2/DT3 X/Y/both: Mean/Standard deviation of the hand velocity on parts DT1/DT2/DT3 on axis X/Y/ both of them.
- Mean Velocity DT2 start: Mean velocity during the first 0.25 seconds of the DT2 part.
- Mean/SD Acceleration DT1/DT2/DT3 X/Y/both: Mean/Standard deviation of the hand acceleration on parts DT1/DT2/DT3 on axis X/Y/ both axes.
- Distances total traveled per time window and total, ratio of minimum movement required to actual
- Total Distance/ Total Distance DT1/DT2/DT3: actual distance travelled during the whole W_i, on parts DT1/DT2/DT3 respectively.
- Minimum distance (final): minimum distance from the center of the gate during the whole W_i movement/ during the final 0.5 sec of the W_i movement
- Movement ratio: actual distance travelled/minimum distance required

The distance and subsequently the velocity and acceleration are measured in the in-game units. Since all four subjects performed their sessions with the calibration settings of the patient, they correspond to the same actual movement.

4 Results

The data consisted of 3 healthy subjects and one subject suffering from a neuromuscular issue that also was under physical rehabilitation at the time those sessions were performed. Each of the subjects had recorded their session within a day, the patient had completed 43 sessions while the others had 24 in total (8 each).

Since the gates are always visible to the users, in some cases the subject has been found to have started moving towards the next gate a few milliseconds prior to reaching the current gate. As a result, this can lead to DT1 segments having 0 duration. For the purpose of this analysis those segments were not taken into account.

The gates were grouped based on the type of movement, vertical, horizontal, diagonal and the direction (e.g. top to bottom etc.) **Fig. 2**. The features were tested for normality using the Shapiro–Wilk test. In cases where the variables were normally distributed the analysis of variation (AOV) was utilized, while in the other cases the Mann-Whitney U test was preferred. The features that were found be statistically significant ($p<0.05$) were selected and had their p-values corrected using the Bonferroni correction. We proceeded by removing the features with corrected p-values above 0.05. Afterwards, the remaining features where checked for correlation among them. Out of those that were found to have a high degree of correlation (0.8), the best performing features were selected.

Results from the analysis of the movement from the right side towards the left side, which involved 67 control gate movements and 86 patient game movements, can be found on **Table 1**.

Table 1. Movement from right towards left

Features	Control		Patient		p-value
	Mean	Sd	Mean	Sd	
DT2	359.20	278.65	702.8	434.5	0.0000005
Mean Velocity DT2 Start	68.85	37.84	47.19	16.66	0.0000107
Mean Velocity DT2X	70.94	31.38	51.55	16.85	0.0000002
Sd Velocity DT2 Y	8.75	13.49	14.25	13.31	0.0000002
Sd Accelaration DT2 X	29.31	21.41	47.74	67.77	0.0000023
Sd Velocity DT3	34.19	16.87	21.60	10.02	0.0000022
Total Distance	108.01	43.84	80.16	27.96	0.0199482

Total Distance T3	60.50	18.81	39.07	10.65	0.0000011
Min Distance Final	4.75	6.68	1.75	1.43	0.0000004
Ratio	4.21	3.68	2.26	0.65	0.0000111

Results from the analysis of the movement from the bottom towards the top, which involved 23 control gate movements and 148 patient game movements, can be found on **Table 2**. It is interesting to note that the majority of important features co-incide in the two types of movements.

Table 2. Movement from bottom towards top

Features	Control		Patient		p-value
	Mean	Sd	Mean	Sd	
Mean Velocity DT2 Start	63.72	34.39	25.99	12.94	0.0000005
Mean Velocity DT2 Y	37.65	27.43	23.44	11.34	0.0000107
Sd Acceleration DT2 Y	23.98	60.63	21.00	22.68	0.0000002
Sd Velocity DT3	39.67	24.30	20.31	7.78	0.0000002
Total Distance	111.2	57.79	66.90	20.32	0.0000023
Total Distance T1	24.50	19.90	11.87	11.85	0.0000022
Total Distance T3	63.63	21.73	36.51	14.77	0.0199482
Min Distance Center Final	7.41	5.20	4.43	2.19	0.0000011
Ratio	2.80	1.54	1.61	0.42	0.0000004

5 Conclusions

The features meanVelDT2Start, meanVelDT2, sdAccDT2, sdVelDT3, totalDistance, totalDistanceT3, ratio are found in both type of movements to have higher values in normal subjects than the patient (with the exception of sdAccDT2X). This is expectable since the patients neuromuscular disorders lead to limited mobility of the upper limps as such the patient's hand movement is moving at a much slower pace. The greater value in the patient's sdAccDT2X suggests that he has trouble maintaining a steady acceleration on the X axis.

This analysis provides a preliminary proof of concept on how to quantify the movement in a meaningful way and express differences between normal and pathological movement.

The next steps are to increase the amount of data available, both for control and patients. Establish a baseline for the healthy population is essential and can lead to a quantifiable evaluation of the patients progress and response to rehabilitation.

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