Digitalization of the Physical Performance Test and Training

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***Abstract*—The measurement of the physical functions of the human body is of big interest, especially after a surgery, after an accident and for disabled or elderly people. After special training or rehabilitation, the progress can be analyzed via measurement. The Modified Physical Performance Test consists of different tasks and with a point system the performance of physical functions can be determined. However, until now this test is carried out with a supervisor and a stopwatch. This leads to inaccuracy, aberrance and missing data. The aim of the digitalization of the Modified Physical Performance Test is to provide objective test results. Wearable sensors, smart objects and computer software were developed to measure the body position and movement. This will help to determine patient progress, trigger timers and calculate a test score. All these factors will eliminate inaccuracy and aberrance and facilitate the task of the supervisor. A training mode was developed, which motivates the patient to further train their balance. This training mode will help to improve future test scores. A clinical trial with ten patients of the Yale rehabilitation unit in Milford hospital was conducted. The outcome of the work showed a great correlation between the digital test score and the evaluation of specialists in the corresponding field of rehabilitation via the traditional Modified Physical Performance Test score. It was shown that the proposed Digitalization of the Physical Performance Test might be used for various patient groups. The test procedure is feasible and offers numerous advantages compared to the traditional test.**

***Index Terms*—IMU, joint replacement, orthopedics, Parkinson's disease, Physical Performance Test, rehabilitation, stroke, wearable.**

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I. INTRODUCTION

A. Problem Statement and Motivation

THE measurement of the physical functions of the human body is of big interest, especially after a surgery, after an accident and for disabled or elderly people. After special training or rehabilitation, the progress can be analyzed via measurement. The Modified Physical Performance Test (MPPT) consists of different tasks and with a point system the performance of physical functions can be determined. However, until now this test is carried out with a supervisor and a stopwatch. This leads to inaccuracy, aberrance and missing data.

B. Aim of the Project

The aim of the digitalization of the Modified Physical Performance Test is to standardize the test results. With the help of wearable sensors, smart objects and computer software, it is possible to measure the body position and movement. This will help to determine patient progress, trigger timers and calculate a test score. All these factors will eliminate inaccuracy and aberrance and facilitate the task of the supervisor.

C. Objective

The main objective of the thesis is the creation of a test to measure the physical performance of patients. The population group consists of different patients, who all struggle to do tasks of daily living. The sub tasks of the test measure different body functions and can give an overview over the areas that the patient struggles with. The end result of the test is a percentage score, that helps to show the abilities of the patient. The test can be used over time to show rehabilitation progress.

After a literature research, the needed sensors for an evaluation of the patient movement have to be defined. The selected sensor hardware has to be combined with an microcontroller and a power source and must be embedded in a case. Additionally, a device to measure balance must be developed. The measurements of the sensors are evaluated at the end of the thesis.

The wearable sensor of the microcontroller has to capture the body movement of the patient and send the measured values to the PC software. The PC software must evaluate those measured body movements of the patient. Additionally, the read data and the test score should be saved to a file. In that way further data analysis can be carried out.

II. LITERATURE, BASICS

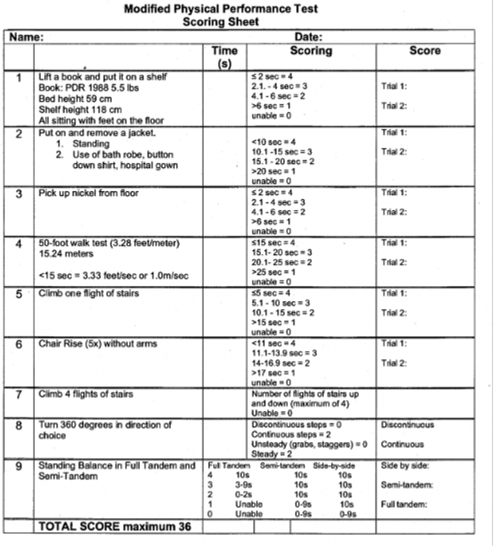
A. Assessment in Rehabilitation

In order to determine the physical status of a patient, it is important to get a test score. In that way, the physical functions of the patient can be determined. Another benefit is that the patients score can be compared over an extended time frame. In that way rehabilitation success can be tracked. The most common test procedures are covered in this section.

The Knee Injury and Osteoarthritis Outcome Score (KOOS) describes the quality of life for a patient with knee related symptoms. The principle behind this test is a self-reported questionnaire. The patients has to answer questions regarding pain, symptoms, function in daily living and sport, and quality of life. The test is only question based, therefore there is no physical test aspect involved. [1]

The MPPT is an important tool to measure the physical abilities of patients after surgeries, strokes, Parkinson's and neurological diseases, chronic pain, as well as movement and gait disorders. The different tasks of the MPPT can be seen in figure 1. However, the measurement with pen, paper and a stopwatch is the current approach to carry out this test. This results in a lot of limitations [2].

The first limitation is the inaccuracy in those manual tests. The evaluator must watch the performance of the patient very closely and measure the time too. This results in a very inaccurate measurement. It is also not guaranteed, that the evaluator judges the patient in a correct way every time the test is taken and human errors can occur. Another limitation is an inconsistency between evaluators. In this way no standardized way of measurement is guaranteed.



Modified Physical Performance Test
Scoring Sheet

Name:			Date:	
		Time (s)	Scoring	Score
1	Lift a book and put it on a shelf Book: PDR 1988 5.5 lbs Bed height 59 cm Shelf height 118 cm All sitting with feet on the floor		≤ 2 sec = 4 2.1. - 4 sec = 3 4.1 - 6 sec = 2 >6 sec = 1 unable = 0	Trial 1: Trial 2:
2	Put on and remove a jacket. 1. Standing 2. Use of bath robe, button down shirt, hospital gown		<10 sec = 4 10.1 -15 sec = 3 15.1 - 20 sec = 2 >20 sec = 1 unable = 0	Trial 1: Trial 2:
3	Pick up nickel from floor		≤ 2 sec = 4 2.1 - 4 sec = 3 4.1 - 6 sec = 2 >6 sec = 1 unable = 0	Trial 1: Trial 2:
4	50-foot walk test (3.28 feet/meter) 15.24 meters <15 sec = 3.33 feet/sec or 1.0m/sec		≤15 sec = 4 15.1- 20 sec = 3 20.1- 25 sec = 2 >25 sec = 1 unable = 0	Trial 1: Trial 2:
5	Climb one flight of stairs		≤5 sec = 4 5.1 - 10 sec = 3 10.1 - 15 sec = 2 >15 sec = 1 unable = 0	Trial 1: Trial 2:
6	Chair Rise (5x) without arms		<11 sec = 4 11.1-13.9 sec = 3 14-16.9 sec = 2 >17 sec = 1 unable = 0	Trial 1: Trial 2:
7	Climb 4 flights of stairs		Number of flights of stairs up and down (maximum of 4) Unable = 0	
8	Turn 360 degrees in direction of choice		Discontinuous steps = 0 Continuous steps = 2 Unsteady (grabs, staggers) = 0 Steady = 2	Discontinuous Continuous
9	Standing Balance in Full Tandem and Semi-Tandem	Full Tandem Semi-tandem Side-by-side 4 10s 10s 10s 3 3-9s 10s 10s 2 0-2s 10s 10s 1 Unable 0-9s 10s 0 Unable 0-9s 0-9s		Side by side: Semi-tandem: Full tandem:
	TOTAL SCORE maximum 36			

Fig. 1. A list of the composition of the Modified Physical Performance Test. The test in this form consists of 9 subtasks [3].

Also, the evaluator can only measure the patient's movements in a very subjective way. The patient's movement can seem very good overall, but individual movements of body parts are hard to judge. For a better detection of the joint position the patient often must change his clothing and wear hospital clothes. Storing, comparing and analyzing the data is causing further inaccuracies. The data is measured by hand and then transferred to a spreadsheet. This is not ideal and can lead to missing or incorrect data. The measurement is not continuous and leads to a lack of data points and less frequent assessment.

B. Digital Assessment in Rehabilitation

There is a big focus on the digitalization of patient assessment and digitalization for training purposes. The following section focuses on these topics and list various examples.

The two biggest focuses of current digital patient assessment lay on gait tracking and balance tracking. In order to measure gait and track steps, the Inertial Measurement Unit (IMU) is a great tool. Especially the included gyroscope and the accelerometer offer the needed capabilities to measure the leg angle and leg acceleration. A typical gait cycle can be seen in figure 2.

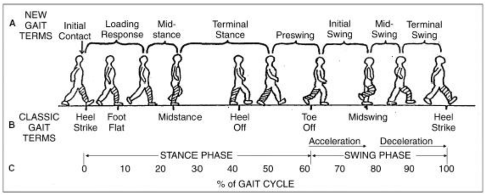


Fig. 2. An overview over the different components of the gate cycle [4].

As it can be seen in figure 2, the highlighted leg changes global position and also the relation to the rest of the body changes. This change reflects in a change of leg angle and a change of leg acceleration. A measurement of those two quantities can give an overview of the current status of the leg in the gait cycle. A possible example approach would be, if the leg angle reaches a certain value and at the same time acceleration in forward direction of the leg is detected, a step is initialized and the initial swing phase of the leg starts. If the angle of the leg goes to 0° and no acceleration is measured, the loading response of the gait can be detected.

Detailed literature for an advanced control algorithm to evaluate stair running performance is shown in [5]. An option to measure foot motion tracking with the use of a convolutional neural network and a six axis IMU is presented in [6]. The potential to calculate an MPPT score automatically while wearing IMU sensors is proposed in [7]. The system uses machine learning for the score prediction. An approach for an exercise in a home based way is presented in [8]. It also focuses on protein intake and persuasive technology for older adults. The approach of a home based High-Intensity Interval Training for Parkinson's patients is presented in [9]. The project aims to be feasible and safe and proves this claims by data collection. An idea for low appendicular lean mass detection in older adults is explained by [10]. The method is called bio-electrical impedance analysis. The validity of low appendicular lean mass detection by using this method is not the best. However the process is able to detect low muscle mass in adults.

III. SYSTEM

A. Hardware

A microcontroller is an integrated circuit which is built in a compact form factor. It usually consists of a processor, inputs/outputs, a memory chip and a clock generator. It is used to control processes or devices in different applications and perform defined tasks. Microcontrollers are used in various embedded systems and control engineering tasks and other fields such as: Automotive, Industrial Automation, Consumer Electronics, Internet of Things (IoT), Aerospace, and Medical Devices.

A good overall understanding of the IMU hardware can be gained in [11]. To detect the angular rate and orientation of a body, the IMU uses the sensor values of accelerometers, gyroscopes, and sometimes magnetometers. They all deliver sensor values on their own, but the real strength of the IMU lies in the combination of those sensor values. When combining the three sensor values, e.g. to measure the angle with a complementary filter or a Kalman filter, the accuracy of the measured angle is increased [11][12].

Force sensors are used to measure the force applied to the sensor surface area. The working principle is the conversion of physical force into electrical quantities, which can be measured by e.g. the inputs of a micro controller.

3D printing describes the creation of a three dimensional object out of various materials. The used materials are plastic, resin, metal, powder, or carbon fiber. The object is created from a digital model and printed layer by layer. A slicing software is used in order to convert the digital 3D model, usually created in a Computer Aided Design (CAD) program, into G-code which the 3D printer can read.

B. Digital MPPT Adaptation

Adaptations of the traditional MPPT have been made, in order to define the most important test, cover all movements needed in everyday life, and include additional sensor data. This helps to get a more objective and detailed score compared to the traditional analog MPPT. The sub tests chosen and adapted from the traditional MPPT are the following: 10 step walk, 4 step stair walk, Turn 360 degree, Chair Rise (5x) without arms, Pick up object while sitting, Pick up object while standing, Balance with feet together, and Balance while in tandem position. In comparison to the traditional MPPT, some tasks were removed or modified.

Those tests cover the most important body movement groups and a variety of different movements of everyday life. The tests and the different metrics are chosen together with rehabilitation workers of the Yale university hospital. Out of the eight tests, the first six use the IMU wearable and the last two use the new balance board adaption.

C. MPPT Sub-Task Definitions

A feature of the software, which is written in Python, is the graphical user interface. It shows detailed information of the sub task results and also the result of the total test.

The PC software also features a Message Queuing Telemetry Transport (MQTT) element. In the case of the PC software it is a MQTT receiver, which receives the wearable string from the MQTT broker. The received string is split into the individual variables and used in the program code. The variables are additionally logged into a text file and saved to the PC hard drive.
The sub task scoring system will take the traditional MPPT timescore into consideration and also a newly measured sensor parameter, also defined as balancescore. At the end of the test, the mean of all sub tasks is calculated and results in a final test score.

For the first sub-task, the patient has to walk ten steps and the passed time is the total time needed. The timer starts automatically as the patient takes the first step. A timescore is generated. Additionally timers are also started as soon as a feet leaves the ground. The time for right foot and left foot is calculated and the ratio between the times. This results in a balance score. The same behavior is also applied for the second sub-task, walking 4 stair steps. For the third subtask the patient has to turn around 360 degree and keep as stable as possible. The balancescore is effected by the chest angles and the patient has to stand as straight as possible while turning around. For the fith sub-task the patient has to go from sitting to standing position five times without the use of the arms. The patient should keep his upper body as stable as possible and do not lean to the left or right. For the next sub-task the patient has to pick up a smart object of the floor and place it on a table while sitting and while standing. This results in two different sub tasks with different score criteria. The last sub-tasks involve balancing in tandem position and while the feet are together.

D. Wearable Software

The wearable software is used in the IMU version of the wearable device and the balance board. The main three parts of the software are the following: MQTT sender, Receive sensor data, and IMU Calibration.

The MQTT sender part of the code uses the WIFI capabilities of the microcontroller(ESP32, Espressif Systems) to connect to a WIFI network and communicate via an MQTT broker, e.g. a mosquitto server. Five topics are defined, one topic for each one of the microcontrollers. The ESP32 tries to connect to the server. If a connection is established, the board begins to read the sensor values. The received values are stored in a string and published to the MQTT server. The string consists of values, each separated by a comma. The values of the IMU version of the wearable are the following: Quaternion w component, Quaternion x component, Quaternion y component, Quaternion z component, Acceleration x direction, Acceleration y direction, and Acceleration z direction. The string values of the balance board software version are the following: Force Sensor 1, Force Sensor 2, Force Sensor 3, and Force Sensor 4. The main quantity measured for the IMU are the quaternions and the linear acceleration for each axis. The force sensor values in the balance board adaptation are read by a reading of four analog values.

E. Balance Game

The balance game acts as a training mode of the project, which helps to train the lower body muscles and balance. The patient is motivated while exercising and practicing in a game. The patient is able to control a character in a virtual environment, that is programmed with the help of the UNITY game engine. In order to not feel like traditional, repetitive recovery exercise, the game offers a game character and the input of the character is provided by the balance of the user. The game features objects, which the user has to avoid. The character moves forward in an automatic way and the user balance input controls move the character to the left or right side of the screen. The input device features the same software and hardware as for the balance assessment of the digital MPPT part of the project.

F. Wearable Design

The wearable, which is used to track the limb and body movement, consists of the following main components: microcontroller (ESP32, Espressif Systems), IMU (BNO055, BOSCH), battery (LP502030 $250\,\mathrm{mAh}$, EEMB), electrical switch (KCD1-101, DaierTek), wires, thermoplastic polyurethane (TPU) case, velcro strap, screws and nuts. For the case of the wearable, 3D print technique is used. The chosen material is TPU. The TPU offers a stable design, which is also able to absorb light impacts.

The installation of the components in the wearable case can be seen in figure 3.

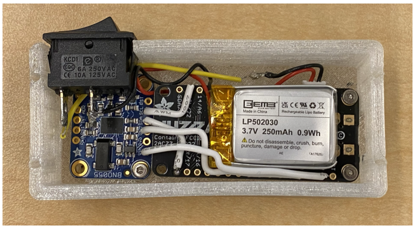


Fig. 3. The wiring of the wearable inside the case. The electrical switch, IMU, ESP32, and battery can be seen from top left to bottom right.

G. Balance Board Design

The balance board adaption features a shoe sole design for each individual foot. The board is used to measure patient balance and consists of the following main components: microcontroller (ESP32, Espressif Systems), force sensors (FSR 406, Interlink Electronics), resistors ($100\,\Omega$), external battery ($10\,000\,\mathrm{mAh}$, EasyAcc), wires, TPU case, TPU soles, screws and nuts.

The sole design can be seen in figure 4. The sole design features eight individual pieces. Four pieces for the right sole and four pieces for the left sole. The reason for the four pieces per side is the sandwich design of the TPU sole. Two sensors are placed in the bottom parts of each side and the top parts are placed on them and fixed via plug connectors.

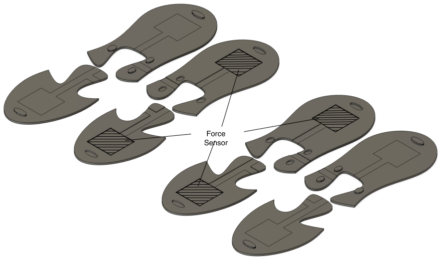


Fig. 4. The CAD design of the sole used to measure balance.

IV. EVALUATION

A. System Evaluation

In order to evaluate the system different tasks are carried out and plots of the measured quantities are created.

In order to evaluate the angle values of the BNO055, the value of the IMU is compared to an encoder. The type of optical rotary encoder is ”LPD3806-600BM-G5-24C” and it offers 600 values per resolution. The encoder is connected to two digital inputs of the ESP32 and the BNO055 is also connected to the same ESP32. The wearable is attached to the lower arm and the shaft of the encoder is also attached to the same rotation point. The evaluation of the measured IMU quantities is done while participating in the digital MPPT in a test environment at Yale Center for Engineering. The values are logged into a text file while performed and plotted afterwards for evaluation purposes.

The comparison between angle value of IMU and encoder can be seen in figure 5. No major lag can be detected. However, there are angle differences when the angles reach their peak values. The absolute mean error is 3.478 degree.

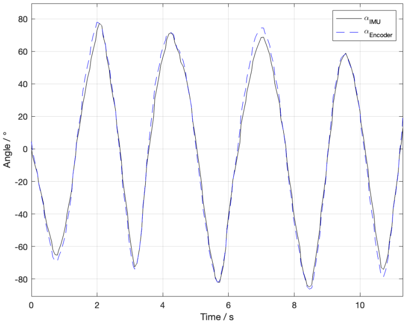


Fig. 5. The comparison between IMU and encoder angle values.

Figure 6 shows the measured data of the walking sub task. Steps are indicated by the peaks of leg forward rotation angle β and leg forward acceleration a_x.

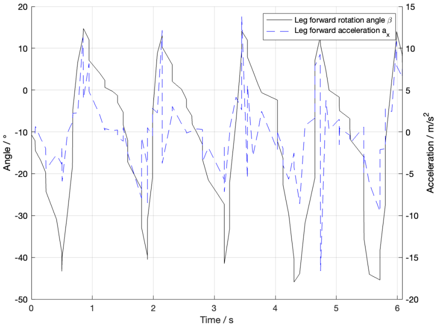


Fig. 6. The measured values of sub task 1.

B. Clinical Evaluation

The project is used and tested in the clinical environment. Patients participate in the digitized MPPT and the result is compared to the traditional MPPT.

In order to let participants take part in the project, a detailed description of the project, the methods used, and the used hardware has to be send to the Institutional Review Board. The project gained full approval of the Yale University IRB. With this consent ten patients of the Yale rehabilitation unit in Milford hospital were able to participate in the clinical trial. The test results of the ten patients are collected and compared to the traditional MPPT test.

In order to see a possible correlation between the two scores, data analysis is used. Before checking the correlation the normality of the values has to analyzed in SPSS. The focus is on the Shapiro-Wilk Test, as this test is ideal for a sample size smaller than 50. The Shapiro-Wilk delivers a Sig. number greater than 0.05 Therefore the collected data is normally distributed.

As normality in the data is detected, the Pearson Correlation method can be used to analyze for correlation. By using SPSS the Pearson Correlation method shows a correlation r of 0.990. This indicates a strong correlation as the maximum correlation yields to a r of 1.

V. DISCUSSION

The results indicate that the used wearable including the IMU offers a great precision to measure movements of the human body. The IMU angle measurement has an absolute mean error of $3.478\,^{\circ}$. The comparison with the ideal value of the encoder show almost no offset regarding the angle value. The data suggest that the body movement in the sub tasks is objectively measurable. Steps, turning, bending can be clearly seen in the data plots and behave as predicted. The study demonstrates a strong correlation between traditional MPPT and the digitized version with an r of 0.990.

The results met the expectations and even proofed almost perfect accuracy. This is expected as the IMU BNO055 is used in a lot of different projects and products and known for the high accuracy and reliability.

These results build on existing evidence of the great use cases for digitalization in patient assessment, training and rehabilitation. Those fields are of big importance and the use of digitalization, sensors, and computer software deliver a lot of benefits to the sectors.

It is beyond the scope of this study to focus on all available patient population groups. The main focus is on joint fracture and joint replacement patients in the rehabilitation center. Also the main focus of the MPPT are patients that are still able to follow simple instructions and do those simple sub tasks.

Avenues for future research include the development of a test for patients with conditions which prevent them from taking part in the MPPT. Such conditions could be if they are bound to a wheelchair, or are not able to follow the instructions for the test procedure. This would enable even more population groups to participate in patient assessment.

VI. CONCLUSION

This research aimed on the development of hardware and software to offer better patient assessment. It is shown that the project offers a fast, standardized and accurate way of assessing the patient's physical performance. The patient results can be compared and progress can be tracked. The IMU angle measurement results are comparable to angle measurements of an encoder. The clinical study and the presented correlation between traditional patient assessment and digital patient assessment show further proof for this better patient assessment.

This digital approach of patient assessment is chosen as the traditional one has too many downsides. The patient movements are not measured, there are human errors involved and the procedure is no standardized. The digital version solves all those problems. The use of an IMU offers a small form factor and accurate results. The results of the digital MPPT match give a good overview over the physical abilities of a patient and match with the expected results.

The clinical study was carried out mainly with joint fracture and joint replacement patients in the rehabilitation center. One option for further studies would be the test on participants with Parkinson's disease or stroke patients. They are also struggling in daily life and the test would suit them perfectly. Another possibility would be the use of the wearable for other approaches such as different medical assessment tests or the use of sensors in combination with a VR headset for rehabilitation purposes.

The project shows that digitization in patient assessment brings many benefits and can be used for a big variety of different patient population groups. The advantages for the patient and rehabilitation worker are immense. The patient feedback is positive and they feel encouraged by the feedback of the computer test in combination with the sensors.

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