Sport Analyzer: Multi-Sensor Portable Device for Data Acquisition and Visualization in Sport Performance and Rehabilitation

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Abstract

In this paper we introduce Sport Analyzer, a battery powered, small footprint device which simultaneously records and displays two important variables for sport performance and rehabilitation: force and velocity signals. This compact and portable apparatus provides connectivity for optical incremental encoders and load cells. The present work includes calibration guides that will allow sport scientists and physiotherapists to build their own hardware and understand how to convert industrial sensors into human movement measuring devices.

Metadata Overview

Main design files: `https://github.com/XaviCanoFerrer/Sport_Analyzer`
Target group: researchers in sport science, physiotherapists and coaches.
Skills required: laser cutting - easy; Mechanical assembly – easy; surface mount components soldering - intermediate.
See section "Build Details" for more detail.

Keywords

Biomechanics, velocity-based training, rehabilitation, sport science, load cell

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Introduction

In sports science, sports medicine and physiotherapy, two of the most valuable mechanical variables that can be used to control performance, fitness and health are force and velocity. The use of certain movements or tests are used to evaluate imbalances that can be related to pathologies or injuries. Sport gesture performance analysis can be as well correlated with a specific training program or method. Among all sensors used for sport performance and rehabilitation, incremental encoders and load cells are some of the most effective to measure velocities and forces associated with physical evaluation tests or exercises. In the case of linear and rotary encoders, they have been extensively used in sport sciences publications to predict the maximal dynamic strength of athletes from the load-velocity relationship [1]; [2]; [3] to evaluate reliability of other velocity and power measuring devices [4]; [5] and to measure concentric and eccentric power in inertial squat performance [6]; [7] between other applications. Load cells have also been used extensively in multiple applications such as: measurement of maximum voluntary contraction (MVC) or isometric strength [8], measurement of instantaneous and average force applied during concentric and eccentric contractions in inertial exercises [6] or characterize forces that change as a function of time or distance such in the case of elastic bands [9]. The aim of the present work is to describe how to manufacture and reproduce a hardware-based device which can display and record signals from both sensors simultaneously.

There are two main products in the market which provide connectivity for load cells and incremental encoders. The pioneer product of the field is the Musclelab™ which interfaces distinct types of sensors with acquisition units that are connected to its specific computer software [10]. Another manufacturer which provides load cell and encoder data acquisition by interfacing both sensors with a computer using an open-source software is Chronojump Boscosystem® [11]. Both products are based on computer software which interfaces with the sensors through a data acquisition unit (Musclelab) or Chronopic (Chronojump). The main differences of the present device in front of these two commercial products are: Sport Analyzer is the only open-source hardware approach without the need of software for the acquisition and visualization, it can be reproduced at cost price, and it is battery powered which enables its use on any environment. On the other hand, Vitruve [12] and Gymaware [13] are products composed of one linear encoder with wireless connection for smartphones or tablets. They present the portability advantage, but they do not have the load cell or the rotary encoder capabilities (Table 1). Sport Analyzer aims to connect the sport science and rehabilitation professionals with the open hardware approach giving to its users more tools in understanding and further hardware customization.

Table 1. Comparison of Sport Analyzer with other available hardware. Cost was obtained from the public prices (Chronojump, Vitruve and Gymaware) or from distributors (Musclelab).

	Sport Analyzer	Chronojump	Musclelab	Vitruve	Gymaware
Load cell	Y	Y	Y	N	N
Linear encoder	Y	Y	Y	Y	Y
Rotary encoder	Y	Y	N	N	N
Battery powered	Y	N	N	Y	Y
Requires computer software	N	Y	Y	Y	Y
Open source software	Y	Y	N	N	N
Open source hardware	Y	Y	N	N	N
GUI for data visualization	N	Y	Y	Y	Y
Load cell and encoder simultaneous acquisition	Y	N	Y	N	N
Cost (GBP)	179.99 (parts)	773.22	2,467.77	339.75	2,353.43

Overall Implementation and design

Sport Analyzer is a programmable, Arduino compatible and battery powered device for simultaneous data collection and visualization of two important variables in sport sciences and rehabilitation which are force and velocity. The device accomplishes this by combining a load cell and optical incremental encoder data acquisition (Figure 1a).

System Architecture

The device has been designed to provide the visualization of force and velocity signals in a thin-film-transistor (TFT) display, which correspond to the sensors: linear or rotary encoder and load cell signals (Figure 1b). At the same time acquires their data and saves it inside a Micro SD card (Figure 1c). It is operated with simplicity, having one button to change the signal displayed and another to place a numeric label associated with the number of sample being acquired. The device is battery operated using a regular 9V alkaline battery which is widely available.

Electronics

The device's main control unit is the Teensy 3.2 development board (Freescale Semiconductor MK20DX256). It has two RJ12 connectors which allow the connections for the linear or rotary encoder and the load cell. Sport Analyzer has a TFT 2.8" display (Adafruit 2.8" TFT LCD with touchscreen breakout board with Micro SD Socket - ILI9341) which also has a Micro SD card socket where the device stores the data collected from the sensors in a txt file. The device has two push buttons, the first one allows the user to switch from displaying the encoder signal (in blue color) and the load cell signal (in red color) on the TFT screen. The second push button increases a counter value to label the first data column of the txt file stored on the Micro SD card and allows the user to label parts of the data, for instance to record different experimental subjects. The load cell conditioning signal is operated by a HX711 (24-Bit Analog-to-Digital Converter (ADC) for Weigh Scales, Avia Semiconductor). The optical incremental encoder signal admits 5V A, B and Z phases connection directly on the Teensy 3.2 pins, which are 5V tolerant. The device is powered using a regular 9V battery (Figure 2).

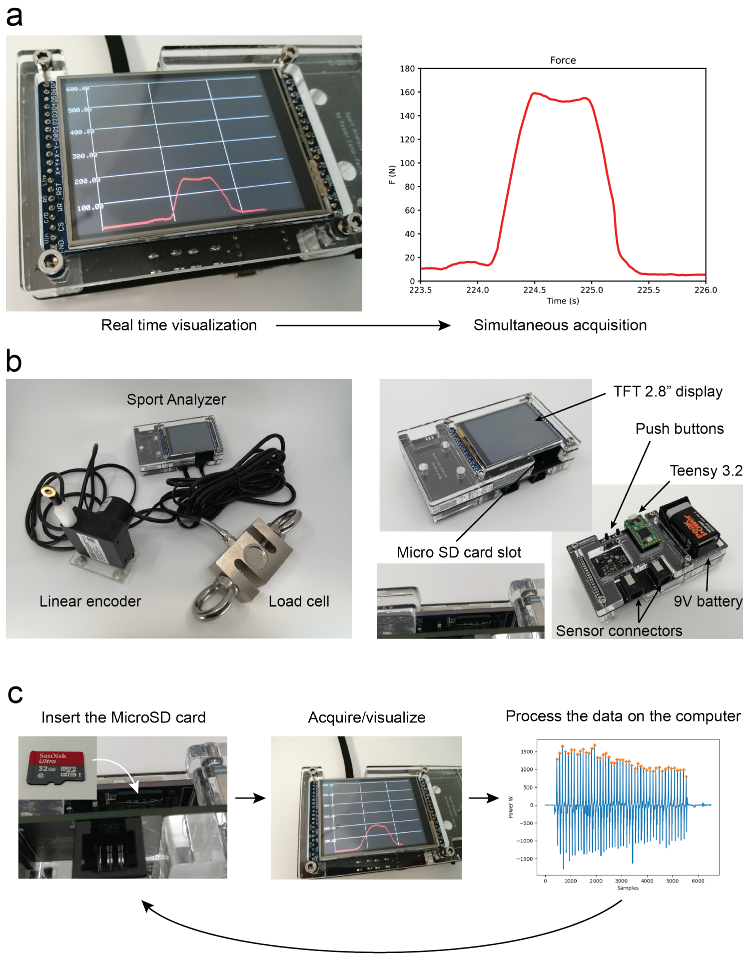

Figure 1: **Concept a.** Sport Analyzer allows simultaneous data visualization and acquisition for further analysis. The figure shows the same signal during the acquisition on the TFT display (left) and after the analysis in a plot from the data extracted from the txt file (right). **b.** The device with the linear encoder and the load cell connected (left) and the main components of the device (right). **c.** The device is conceived to have an SD card logging data from both sensors constantly while is being used. After the visualization, the Micro SD card can be connected to the computer and the data can be analyzed.

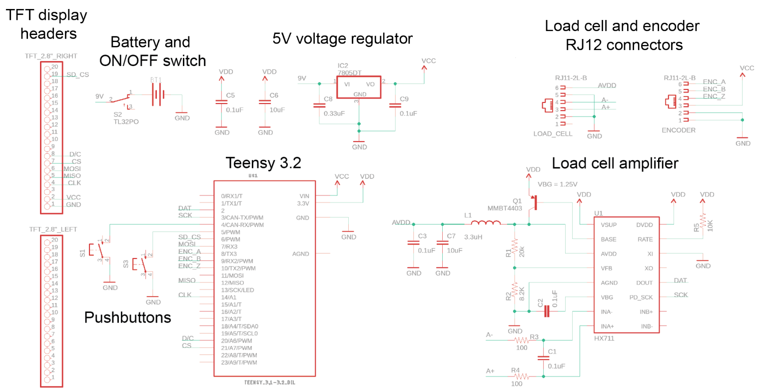

Figure 2: **Electronic schematics of the device.** Sport Analyzer schematic is composed by the Load cell amplifier circuit, the Teensy 3.2 development board, two push buttons, an ON/OFF switch, the two RJ12 sensor connectors, a 5V voltage regulator which converts the 9V of the battery and the TFT display pin headers.

Sensors

The optical incremental encoder used in the present work is a Wisamic with 600 pulses per revolution with a response frequency of 0-20 kHz and a maximum speed of 6000 rpm. On the other hand, the load cell is an S-type load cell which allows compression and tension forces measurement. The load cell's main electrical properties are defined by the sensitivity of 2.0 mV/V, repeatability of ±0.02 %FS, linearity of ±0.02 %FS, a measuring range of 4.9-4900 N and input impedance of 350±10 Ω.

Enclosure

The device case has been designed to be manufactured either laser cut or 3D printed. It is a minimalist design to protect the device integrity with minimum complexity. It is composed of three layers: top, middle and bottom and M3 screws and hexagonal spacers.

Firmware

The firmware that is uploaded on the Teensy 3.2 is composed by its main file: `Sport_Analayzer_1.0.ino` and it uses six libraries: the `SPI` library [14], the `ILI9341_t3` library [15], the `Bounce` library [16], the `Encoder` library [17], the SD library [18] and the `HX711` library [19]. Additionally, there are essential parts of the firmware that are based on the work of other developers, these functions are: the method that generates a graph for TFT displays [20] and the application we use to generate the code from the Sport Analyzer logo bitmap [21].

The main loop function of the firmware runs inside a three hundred samples `for` loop which is enough to fill the horizontal axis of the screen. For every iteration, a reading of the push buttons, load cell and encoder is performed and saved on the Micro SD card by calling a function called `save_sd_card()`. The velocity is computed at every defined interval, which is by default 10 milliseconds and then the graph function is called displaying the desired signal. After the last iteration of the `for` loop the TFT display is restarted.

The variables to change the maximum range of the vertical axis can be found on the firmware lines 21 and 46 `v_max` and `F_max`. Two Boolean variables called `linear_flag` and `rotational_flag` enable the linear or the rotational conversion of the encoder pulses.

(2) Quality control

Safety

The device has been designed to use a 9V battery as a power supply, it draws 120 mA DC and it is considered low current, but the electrical hazard exists, and it must be taken seriously. Precautions must be taken to place the battery on the battery holder as the device has no inverse polarity protection and it would damage the device permanently. Some safety considerations must be taken with the load cell maximum load which is 4900 N (500 kg) proposed in the present work. The same applies for the maximum cable extension of the linear encoder which is up to 1.5 meters. Those limits will change if other measurement equipment is chosen.

Calibration

The calibration procedure of the device has been done using a `calibration.ino` program, this piece of code can be found on the calibration folder. It displays the raw values of the sensors connected to the Sport Analyzer. In the case of the load cell, it can have positive or negative values corresponding to an extension or compression stress. In the case of the encoder, the value corresponds to the absolute number of pulses related to its angular position. Two spreadsheets are provided on the calibration folder of the repository to re-calibrate the load cell and the incremental encoder in case other sensors are chosen.

Load cell calibration

The load cell (Wytino) was calibrated in the first place by measuring its weight with a scale (Kern ECB 50K50), which is approximately 0.8 kg. The value of the load cell's weight is added on the measurements together with seven weights of known values attached vertically with the load cell measuring the vertical deformation (Figure 3a). The value that corresponds to the zero measurement is the value displayed when the load cell is in horizontal position. The relationship of the load cell reading (value of voltage converted by the 24-bit ADC) and the weight is linear with R=1 and force function F = 0.0011x - 1.248 (Figure 3b).

Linear encoder calibration

The linear encoder is composed of two components, the rotary incremental encoder (Wisamic) and the wire draw mechanism (Calt) which converts the rotary

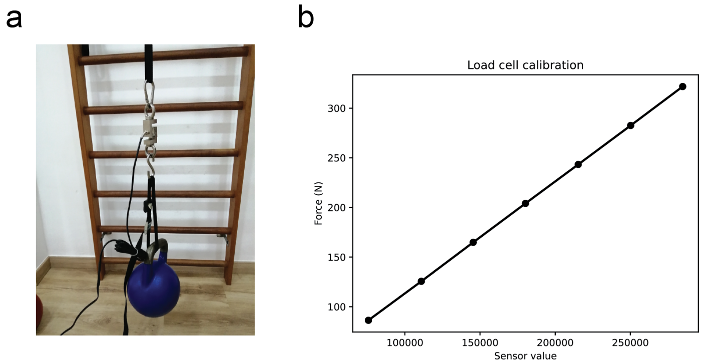

Figure 3: **Load cell calibration process. a.** Seven loads of known values are suspended from the load cell. **b.** Load cell calibration function.

movement into a spring-loaded linear movement. Its calibration has been performed by placing a measuring tape on a flat surface and measuring 15 times a 0.5-meter distance (Figure 4a). Figure 4b shows a low standard deviation of pulses within the target of 0.5-meter distance. The resulting resolution is calculated as the average travel in mm divided by the average number of pulses which results in 0.063 mm per pulse.

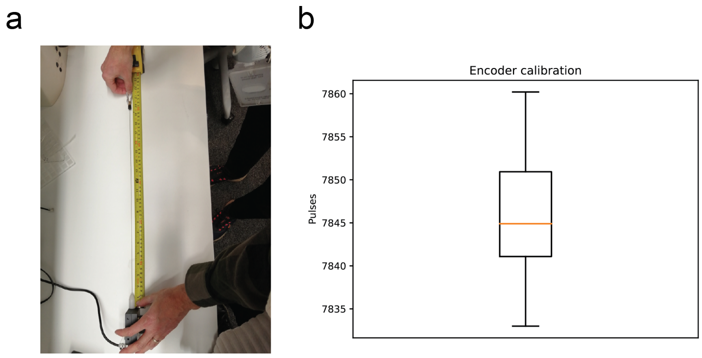

Figure 4: **Encoder calibration process. a.** The process consists on repeatedly (N = 15) measure 0.5 m distance and collect the number of pulses at the maximum extension. **b.** The bar plot shows the mean and standard deviation of the pulses that corresponds a cable extension of 0.5 m.

Rotary encoder calibration

In the case of the rotary encoder no calibration is needed as the angular position measurement is the intended use of it. The proposed optical incremental encoder (Wisamic) has 600 pulses per revolution which corresponds to 2400 detecting rising and falling edges. The resolution is given by the ratio between 2π radians and the number of pulses which corresponds to approximately 2.62 mrad/pulse.

General testing

Additional information from the device has been evaluated experimentally. The device weighs less than 200g without the sensors and the battery (Fisher Scientific CSC 501). The electric current consumption (120 mA) has been measured using a Hameg HMP 4040 power supply at 9V. The sampling period of Sport Analyzer acquiring both sensors and displaying the signal has been measured the difference in milliseconds between samples logged on the SD card, it is approximately 13 milliseconds. The main characteristics are summarized in Table 2.

Table 2. Sport Analyzer main characteristics.

	Value	Units
Sampling Frequency	78	Hz
Weight (without battery)	194.4	g
Power	1.08	W
Autonomy (standard alkaline 9V battery)	4.5	h
Linear encoder resolution	63	μm
Load cell resolution (Theoretical using a 24 bit ADC)	0.1	mN
Rotary encoder resolution	2.6	mrad
Maximum encoder measuring distance (Supplier information)	1.5	m
Maximum load cell measuring force (Supplier information)	4.9	kN

(3) Application

Use case(s)

We provide evidence on four differentiate cases where Sport Analyzer is an essential tool to show professionals and researchers data either for visualization or interpretation.

Combined measurement of angular velocity and force in inertial resistance training

The first use case provided is an example using the load cell simultaneously with the encoder in the rotary encoder configuration to acquire angular velocity and force at the same time in a unilateral row with a conical/inertial pulley (Figure 5a). The encoder is set up in rotational mode and coupled with the inertial pulley shaft (RSP conic).

Measurement of forces in suspension training devices

The device can provide a clear picture of the data that cannot be measured in any other way such as dynamic exercises performed using rigid devices, for instance suspension training devices where the force is usually unknown because it is applied against a rigid strap. Figure 5b shows the force over time of eccentric and concentric contractions, which can be clearly identified in the hip extension full cycle. The plotted signals are an average of three repetitions per leg.

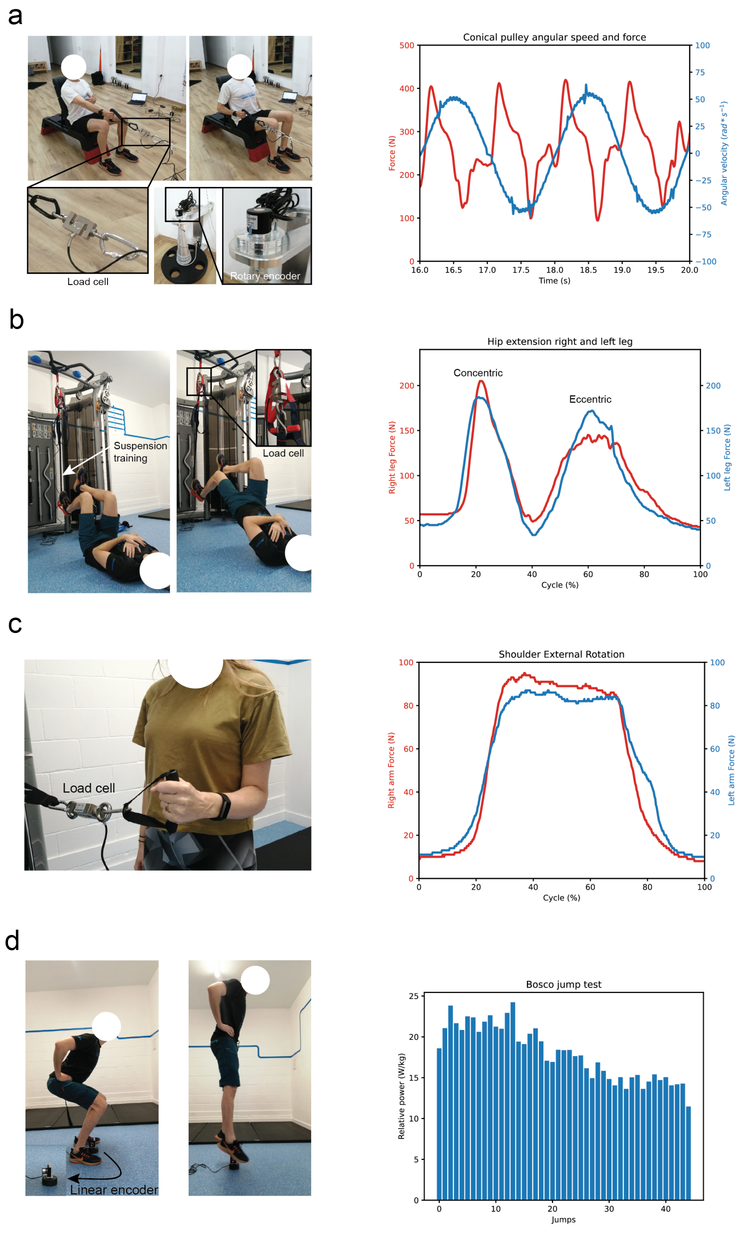

Figure 5: **Use cases a.** Unilateral row in an inertial conical pulley with simultaneous acquisition of force and angular position. **b.** Hip extension performed in a suspension trainer with a load cell attached. **c.** Shoulder external rotation isometric maximum voluntary contraction against a load cell. **d.** Counter movement jump (CMJ) with a linear encoder measuring linear displacement and velocity which allows the estimation of the relative power of each jump performed during a 60 second Bosco test.

Monitoring of isometric contractions in physiotherapy evaluation and treatment

In Figure 5c we present a comparison between right and left arm force during maximum voluntary contraction (MVC) in the isometric force in the shoulder external rotation (the plotted signals are averaged across 3 repetitions). This is an example of how it can be used to find differences between healthy and injured joints, in this case could be used to identify difference related with shoulder impingement syndrome or EMG signals associated with shoulder isometric muscular contractions [22]. This example is extremely valuable to show that the device can provide real time feedback to rehabilitation professionals and physiotherapists during isometric exercises or evaluations with patients.

Measurement of velocity and relative power

In the last example it is shown how the device can be used to determine the relative linear power during a physical movement such as vertical jumping. Figure 5d shows its performance recording a Bosco jump test which consists of repetitive counter-movement jumps (CMJ) for 60 seconds [23]. From this experiment several valuable indicators can be extracted: such as the relative power and the fatigue index between 0 and 15 seconds and between 0 and 60 seconds. This has been used for decades to classify and compare athletes from different disciplines and standardize their performance level.

Reuse potential and adaptability

In the way the manufacturing is proposed, the main components such as the Teensy 3.2 and the Adafruit TFT display can be reused for other devices or for future versions of the Sport Analyzer, reducing the components needed for future versions as they are attached using pin headers. The modularity of the sensor connection ensures that the sensors can be connected to future devices.

(4) Build Details

Availability of materials and methods

The complete bill of materials can be found on the Sport Analyzer repository as well as the detailed assembly instructions. All the electronic components are widely available, and the device has been designed to be easily reproduced, simple to use and customize, durable and robust.

Ease of build

All the electronic components are soldered on the PCB without the need of stripping or crimping any wire and providing a more robust and durable design. Some of the electronic components are surface-mount technology (SMT) components and therefore the use of tweezers to hold them when soldering is recommended. The mechanical components have been designed to be manufactured with any technique: the three case components and the encoder base are 2D designs with a certain height which can be achieved laser cutting acrylic of different thicknesses or with any 3D printer (Figure 6).

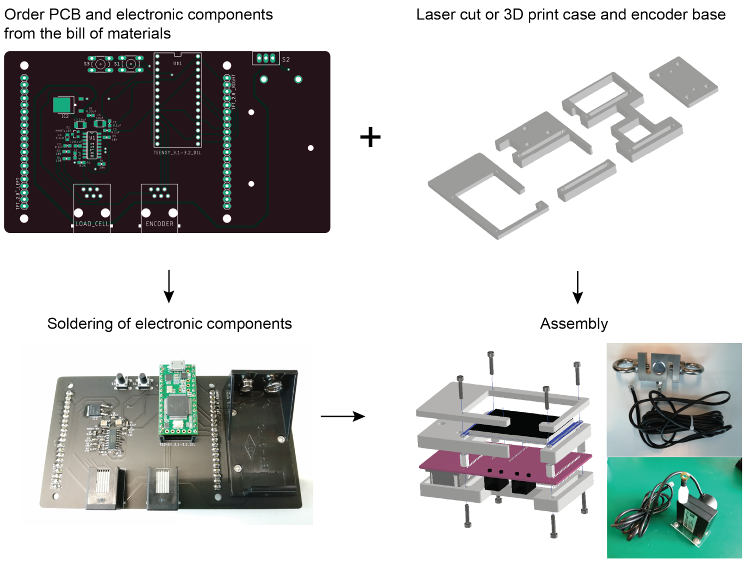

Figure 6: **Manufacturing process workflow diagram.**

Operating software and peripherals

The firmware is uploaded on the Teensy 3.2 development board using the Arduino IDE and their add-on Teensyduino developed by PJRC. It can be found on the "Firmware" folder of the main repository.

Hardware documentation and files location:

Archive for hardware documentation, modifiable design files, software and build files.

Name: GitHub

Persistent identifier: `https://github.com/XaviCanoFerrer/Sport_Analyzer`

License: GPL-3.0 License

Date published: 25/02/2022

Publisher: Xavier Cano-Ferrer

(5) Discussion

Conclusions

This article introduces the design of an open-source device which allows monitoring and recording of two of the most important variables to measure patient's health in physiotherapy and athlete's performance. It introduces the sport science and rehabilitation professional communities into the world of making, understanding, and customizing their own measuring hardware devices. The device also opens the perspective of hacking the existing strength and resistance training equipment to attach the sensors described and record or visualize the variables of interest. In summary, Sport Analyzer can help a wide variety of professionals to collect data for their scientific studies and their daily athlete/patient monitoring by being able to extract mechanical impulse, mechanical work, muscle concentric and eccentric contraction power, maximum voluntary contraction (MVC) in isometric muscle contractions, angular and linear velocities, among others.

Future Work

The next future improvement that is currently taking place is adapting the platform to the newest Teensy version, the Teensy 4.0, which is currently under testing. We are also working on a version compatible with the existing Chronojump hardware and software. Joining forces with Chronojump ensures the availability and improvement of the device with future improvements under the same open source license. Some of the future improvements we are currently working on are: Menu, vertical axis auto-scaling, files organized in folders, during the capture the device will show the name of the subject, the capability to detect changes from concentric to eccentric movements, set the zero in inertial machines, display real time power by multiplying force and velocity, tared force for exercises where a limb weight is involved but it does not have to be measured, the possibility to add a force goal which is displayed on the screen as a horizontal line and be able to import or export data to the Chronojump software.

Paper author contributions

X.C-F. conceived the presented idea, designed the hardware, wrote the firmware and analyzed the data. X.P-C. contributed to the firmware and hardware. X.C-F., X.P-C., J.M.P-R., X.D.B.F. acquired the data, discussed the results and contributed to the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

References

[1] Bruno Bazuelo-Ruiz, Paulino Padial, Amador García-Ramos, Antonio J Morales-Artacho, María T Miranda, and Belén Feriche. Predicting maximal dynamic strength from the load-velocity relationship in squat exercise. *The Journal of Strength & Conditioning Research*, 29(7):1999–2005, 2015.

[2] Francesco S Sella, Daniel T McMaster, Christopher M Beaven, Nicholas D Gill, and Kim Hébert-Losier. Match demands, anthropometric characteristics, and physical qualities of female rugby sevens athletes: a systematic review. *The Journal of Strength & Conditioning Research*, 33(12):3463–3474, 2019.

[3] Laurent Bosquet, Jeremy Porta-Benache, and Jérôme Blais. Validity of a commercial linear encoder to estimate bench press 1 rm from the force-velocity relationship. *Journal of sports science & medicine*, 9(3):459, 2010.

[4] Roland van den Tillaar and Nick Ball. Validity and reliability of kinematics measured with push band vs. linear encoder in bench press and push-ups. *Sports*, 7(9):207, 2019.

[5] Amelia Ferro, Pablo Floría, Jorge Villacieros, and Alejandro Muñoz-López. Maximum velocity during loaded countermovement jumps obtained with an accelerometer, linear encoder and force platform: A comparison of technologies. *Journal of biomechanics*, 95:109281, 2019.

[6] Víctor Illera-Domínguez, Sergi Nuell, Gerard Carmona, Josep M Padullés, Xavier Padullés, Mario Lloret, Roser Cussó, Xavier Alomar, and Joan A Cadefau. Early functional and morphological muscle adaptations during short-term inertial-squat training. *Frontiers in physiology*, 9:1265, 2018.

[7] U Lindemann, P Farahmand, J Klenk, K Blatzonis, and C Becker. Validity of linear encoder measurement of sit-to-stand performance power in older people. *Physiotherapy*, 101(3):298–302, 2015.

[8] Andrea Macaluso and Giuseppe De Vito. Comparison between young and older women in explosive power output and its determinants during a single leg-press action after optimisation of load. *European journal of applied physiology*, 90(5):458–463, 2003.

[9] Alex D Fuentes, Connor J Smith, and Todd C Shoepe. Loading patterns of rubber-based resistance bands across distributors. *Sports*, 7(1):21, 2019.

[10] Musclelab™. https://www.musclelabsystem.com.

[11] Chronojump boscosystem®. https://chronojump.org/.

[12] Vitruve. https://vitruve.fit/.

[13] Gymaware. https://gymaware.com/.

[14] Paul Stoffregen. Spi library for teensy arduino ide. https://github.com/PaulStoffregen/SPI.

[15] Paul Stoffregen. Optimized ili9341 tft library. https://github.com/PaulStoffregen/ILI9341_t3.

[16] Thomas O Fredericks. Debouncing library for arduino and wiring. https://github.com/thomasfredericks/Bounce2.

[17] Paul Stoffregen. Quadrature encoder library for arduino. https://github.com/PaulStoffregen/Encoder.

[18] Paul Stoffregen. Sd library. https://github.com/PaulStoffregen/SD.

[19] Bogdan Necula. An arduino library to interface the avia semiconductor hx711 24-bit analog-to-digital converter (adc) for weight scales. https://github.com/bogde/HX711.

[20] Kris Kasprzak. Functions to draw graphs on lcd. https://github.com/KrisKasprzak/GraphingFunction/blob/master/Graph.ino.

[21] Jasper van Loenen. Tool to change images into byte arrays. http://javl.github.io/image2cpp/.

[22] Darren Reed, Mark Halaki, and Karen Ginn. The rotator cuff muscles are activated at low levels during shoulder adduction: an experimental study. *Journal of physiotherapy*, 56(4):259–264, 2010.

[23] C Bosco and P Luhtanen. komi, pv,(1983). a simple method for measurement of mechanical power jumping. *European Journal of Applied Physiology*, pages 273–282.