Development of a Force Sensor for Biomechanical Simulations of a Cycling Activity

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Abstract— Knowing the forces applied to the pedals during a cycling activity is of great importance in the field of biomechanics when calculating the loads acting on the joints. A load cell-based force sensor was designed for this purpose since the force plate fixed to the floor in gait laboratories cannot be used to measure the reaction forces on the bicycle pedal due to physical constraints. To investigate the accuracy and precision of the force plate, a two-stage experiment, static and dynamic force measurement tests were designed. First, the first static measurements were carried out with standard loads of 1000 g, 1200 g, 1500 g. To understand the behavior of the sensors under dynamic loading, dynamic measurements were conducted while the designed force sensor is attached to the bike pedal while using a commercially available power meter simultaneously to cross-validate the measured forces. Standard loads of 1000 g, 1200 g, and 1500 g were measured as 1020 ± 2 g, 1196 ± 2 g, and 1512 ± 1 g respectively. To assess the agreement between measurements Bland-Altman plot analysis was carried out. The Bland-Altman plots showed that the force platform is appropriate for both measuring static loads and dynamic loads. The collected data via this custom-made, affordable force sensor was successfully fed into the biomechanical modeling software to calculate the joint reaction forces.

Keywords—Load Cell; Force Plate; Power Meter; Verification; Validation; Biomechanical Modelling.

I. INTRODUCTION

In biomechanical modelling, it is crucial to collect data to model the investigated activity accurately. Motion capture systems (MOCAP) are utilized to capture the kinematic information to understand the motion by extracting coordinates of the limbs. For kinetic inputs, external forces should be included properly. For example for gait activities, force plates are utilized to include the gait activities, as it is crucial to accurately include the reaction forces between the human and their environment [1]. However, force plates fixed to the ground in gait laboratories cannot be used to measure the reaction forces for modeling of cycling activities. As the reaction forces between the person and the environment occur at the surface of the saddle and the pedals. Therefore, a portable force plate is needed. For this reason, we searched for an economical solution to measure the reaction forces at the pedals and provided a custom-made solution by designing an economical force sensor to use in biomechanical applications for cycling simulations in our state-of-the-art motion capture systems and biomechanics laboratory of mechanical engineering department.

The most common approach to measuring the force applied to the pedals is to measure the deformation occurring at the contact point as a result of the applied pressure. For this purpose, it is advantageous to use load cells, due to their low cost and ease of use compared to other sensors. A load cell is a device that is used to measure or sense the forces and moments applied on the platform where it is placed [2]. The most common type of load cell is the strain gauge. Strain gauge load cell types consist of thin foil resistors attached to various types of metals depending on the application, and they are the main sensing elements in the load cell [2]. Exerted force on the foil causes deformation or strain, and the intensity of this strain is proportional to the change of electrical resistance of the foil. So that any change in the current could be related to force [2]. Once measured accurately, the pressing force on the pedals could be used to calculate the torque relative to the center pivot point, by multiplying the crank distance. Although commercially available power meters could be utilized to estimate the torque exerted by the cyclists, these power meters are not economical, and they are mostly exported from foreign countries, making it non-affordable. For this reason, in this study we are offering a native and national custom-made-solution.

In this study, we designed a force sensor and calibrated using static weights first. The experiments were carried out with standard loads of 1000g, 1200g, and 1500g. Upon obtaining promising result, the second stage of study for understanding the behavior of the sensors under dynamic loading. To compare against, a commercially available power meter used by elite cyclists is utilized. The results were compared to identify the differences of the systems. An experiment was conducted using a marker-based MOCAP system while collecting data through the custom-made sensor to feed data into the biomechanical modelling software (AnyBody [3] and OpenSim [4]) to calculate the joint reaction forces as a feasibility study to check for its functionality. Bland-Altman analysis is used for measuring the fit between the output of two system in which one is treated as a gold standard, using two quantitative measures by calculating the mean difference and establishing the boundaries of agreement [5]. In this study, to assess the

2022 Medical Technologies Congress (TIPTEKNO) | 978-1-6654-5432-2/22/$31.00 ©2022 IEEE | DOI: 10.1109/TIPTEKNO56568.2022.9960221

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limits of agreement between measurements Bland-Altman analysis was conducted.

II. MATERIALS AND METHODS

In this study, an in-house built force sensor is used to measure the applied force. The main sensing component of the force sensor is the strain gauge. When the force is applied to the sensing element, its electrical resistance varies based on the intensity of the force, causing a change in the electrical signal. This change in the signal is related to the force applied. The Force-sensor has four strain gauges in a Wheatstone bridge configuration. The capacity of the force sensor is 100 kg. The frequency of the force plate is set to 80 Hz.

The electrical signals generated by the load cells were in the millivolts range, therefore signal amplification was required. This was achieved by using The HX711 Weighing Sensor (Figure 1) that has a HX711 Weighing Sensor Module consisting of HX711 chip, which is a 24bit A/D converter (Analog to digital converter). The HX711 module amplified the low electric output of the LCs and then this amplified & digitally converted signal was fed into the microcontroller (Arduino) to derive the weight.

The load cell is connected to the HX711 Load cell Amplifier using four wires (as shown in the image as Red, Black, White, and Green/Blue). Below are the connection details and the diagram (Figure 1).

Red wire is connected to E+, black wire is connected to E- , white wire is connected to A- , green wire is connected to A+.

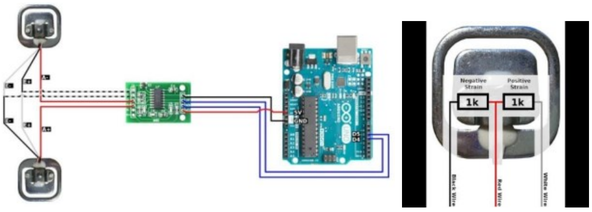


Fig. 1. Connection of Diagram

For further processing and transfer of information, the connection of HX711 to Arduino UNO (Arduino LLC) which is a microcontroller platform with open-source software and hardware, was carried out. For this purpose, power contacts GND and VCC HX711 were connected to the points GND, and 5V POWER connector module of Arduino UNO, and contacts DT and SCK were connected to points A1 and A0 connector ANALOG IN. Load sensor HX711 through the controller Arduino UNO could be connected to the computer, using the USB port and standard libraries for Arduino. The resistance value of strain gauge between the outer wires is twice the resistance between the middle wire and the outer wires. The resistance between the white and black wires is 2K ohm, and between the white and red is 1K ohm (Figure 2).

The power meter used in this study for cross validation purposes is a commercially available product used by elite cyclists, Favero Assioma UNO Power Meter Pedals are shown in Figure 3. Assioma power meter pedals use 8 strain gauges placed around pedal axel to measure the force or torque, then they measure cadence using special type of integrated gyroscope capable of detecting the instant angular velocity during the entire pedal stroke [4]. The product of cadence and torque gives the pedal power.

Fig. 2. Favero Assioma UNO Power Meter Pedals.

A. Calibration

For calibration, the zero (tare) value is read and calibrated to a mass value. Calibration ensures that the load cell is calibrated with a known mass each time it is used, to provide a best estimate of the mass of objects whose mass is unknown.

The calibration was made under linearity assumption using Equation 1. to implement the calibration with an Arduino board and the load cell. The equation for a line is:

$$y = mx + b \tag{1}$$

Where x is the reading from the HX711's ADC, y is the known mass, m is the slope of the calibrated line and b is the intercept where y=0, which is also a 'tare' point

If dummy points x_0, y_0 are used as one point on the line, and x_1, y_1 are used as the second point on the line, both m and b can be defined in terms of those known masses and ADC values:

$$m = \frac{y_1 - y_0}{x_1 - x_0} \tag{2}$$

For zero weight, the reading is zero, hence $y_0 = 0$, which simplifies the expression above:

$$y = \left(\frac{y_1}{x_1 - x_0}\right)(x - x_0) \tag{3}$$

Since strain gauges linearly relate strain to force applied, we are able to use a linear relationship when calibrating the load cell.

B. Static Test

After the calibration, standard loads of 1000, 1200, 1500 grams were used to examine the behavior of the force sensor under static loads. These specified weights were weighted three times, leaving the loads on the sensor for 5 second. The resulting data was saved in .xlsx file format. To assess the agreement between the standard loads and the force plate data, Bland-Altman [5] agreement analysis (α=0.95) was performed by taking the average of three repetitions.

C. Dynamic Test

To understand the behavior of the force plate under dynamic loads, the force platform was fixed to the right pedal of the bike. A power meter pedal (Favero Assioma UNO UNO) was mounted to the left pedal of the bike. For in vivo tests, ethical approval was obtained from the Izmir Ataturk Research and Training Hospital. The experiment subject (44 years, 70.8 kg, 180 cm) warmed up in 3 minutes. The saddle height was settled according to subject anthropometry. Since the pedal power meters need an additional bike computer unit to record and extract the pedal power, the information was transferred to the computer via Zwift software (Zwift Inc., California, US). Zwift is a multiplayer online training application enabling users to connect their training devices via head units. After connecting the pedals to Zwift via Bluetooth as a power meter, they automatically record any movement and force value when the cyclist presses the pedals. During the experiment, volunteers are asked to press the load cell and pedal power meters at the same time, so that they are synchronized. The subject was asked to sit on the saddle and cycle at his own pace for 30 seconds.

III. VALIDATION

The crank rotation during pedaling motion ideally takes place in a two-dimensional plane. We expect that any point on the crank, except the pivot of crank rotation, describes a perfect (sampled) circular trajectory. The angular position of the crank is obtained from the trajectory of a point representing the angular position of the crank. In the same way, the angular position can be calculated from the trajectory described by a point on the pedal, provided that the point is on the pivot of pedal rotation.

The total force Ftotal applied to the pedal is the sum of all vector forces, see Figure 3, produced by the contractions and extensions of the leg and hip muscles which can be decomposed into normal and shear forces, Fn and Fs, respectively. The force Fn is normal to the force platform surface and the shear force Fs is parallel to the surface. Perpendicular parts of these forces create a torque around pivot point of pedal crank arm.

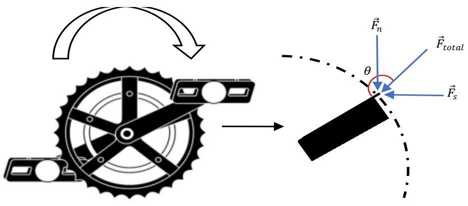


Fig. 3. Free Body Diagram of the Pedal

$$\vec{F}_{total} = \vec{F}_n + \vec{F}_s \tag{4}$$

The torque describes the effect of a force on the rotational motion of the pedal pivot point about the axis on the bearing. Mathematically, torque is the cross product of the lever-arm length vector.

$$\|\tau\| = \left\|\vec{L}_c \; x \; \vec{F}_{total}\right\| = F_{total} L_c \tan(\vartheta) \tag{5}$$

τ: Torque (N.m)

L_c: Level arm (m)

F_{Rn}: Normal component of resultant force (N)

F_{total}: Total force (N)

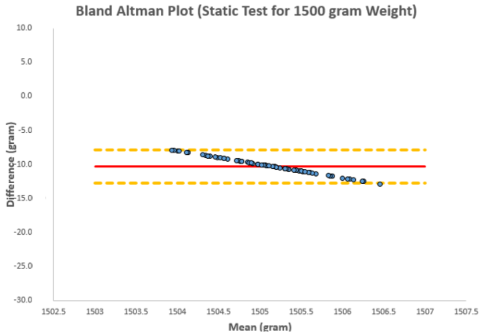
ϑ: Angle between F_R and L_c (in radians)

Torque is a measure of how much a force acting on an object causes that object to rotate and power produced by torque is a product of torque and rotational speed (i.e. cadence). By means this, resultant force can be calculated as following:

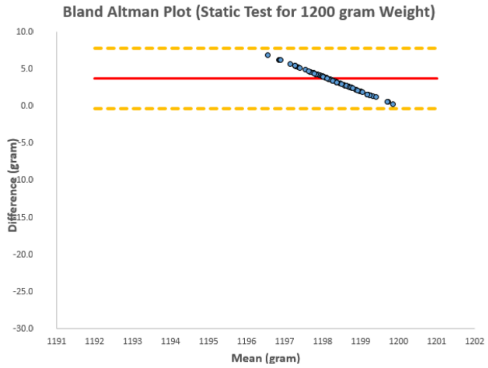
$$F_R(N) = \frac{Power(watts)}{\left(candance(rpm)\; x \frac{2\; x\; \pi}{60(seconds)}\right) * L_c(meter)} \tag{6}$$

Since power meter pedals (Favero Assioma UNO) record the measured data as power output of pedals, to compare them with output of force sensor, they are converted into force via using Eq. (6). After conversion, outputs of two measurement method were compared with Bland-Altman agreement analysis with confidence level of 95 percent (α=0.95) [6].

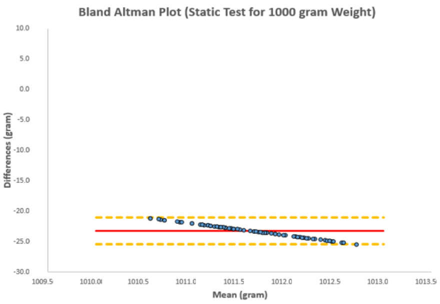
IV. RESULTS



(a)

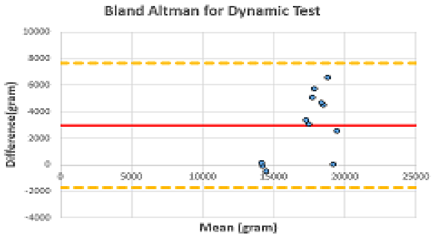


(b)

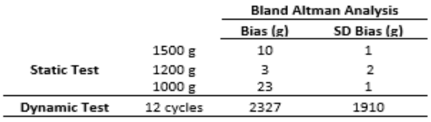


(c)

Fig. 4. a) Bland Altman Plot for Static Test (Static Test for 1500 g Weight), b) Bland Altman Plot for Static Test (Static Test for 1200 g Weight), c) Plot for Static Test (Static Test for 1000 g Weight)



(a)



		Bland Altman Analysis	
		Bias (g)	SD Bias (g)
Static Test	1500 g	10	1
	1200 g	3	2
	1000 g	23	1
Dynamic Test	12 cycles	2327	1910

(b)

Fig. 5. a) Bland Altman Plot for Dynamic Test (12 cycles), b) Bland Altman Analysis of Tests

Table 1. AVERAGE VALUES OF STATIC LOADS

Loads	Trail 1		Trail 2		Trail 3	
	Average (g)	STD (g)	Average (g)	STD (g)	Average (g)	STD (g)
1000 g	1023	11	1024	15	1022	17
1200 g	1196	21	1198	15	1198	15
1500 g	1510	13	1511	14	1510	11

Average values and standard deviation of each trail are given in Table 1. Deviation in trail is approximately % 0.1 for each trail and each load. Results of dynamic test for 12 cycles are 18752 ± 2755 g for pedal power meter and 15790 ± 1449 g.

The results of Bland Altman analysis are shown in Table 1. The mean differences and standard deviation for static tests are low. However, the mean difference and standard deviation of dynamic test is high,

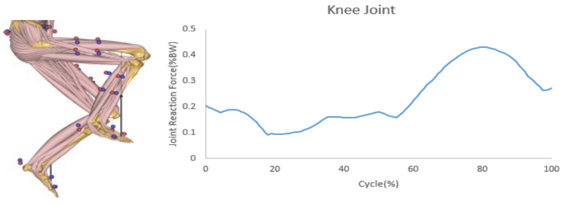


Fig. 6. a) AnyBody Model , b) Anteroposterior Reaction Force (Vertical) of Knee Joint

In Figure 6 a-b, the Anybody model and its output are provided. The intended use of this force sensor is to provide input to biomechanical modelling software AnyBody (AnyBody Technology A/S, Aalborg, Denmark). Measurement of the force sensor was embedded in AnyBody by using xml file, force vector is identified on metatarsal 2 bone as shown in Figure 6 a, demonstrating that force sensor can be used in the biomechanical modeling software successfully.

V. DISCUSSION

The designed force sensor is intended to be used in activities where high loads are applied such as cycling. In this study, the acceptance level for the force sensor's accuracy is set as 5 % from true value for static loads. This corresponds to 50 grams for 1000 grams. The results show that deviation is below 5 % for each weight. The static test results show that the force sensor provides desired measurement values under 1-D loading. As shown in Table 1, the mean difference of the sensor was found to be 2327 g. this level of deviation from the pedal power meter is high when compared to the static test results since these values is approximately 15 % of the maximum force, applied by the cyclist. This type of deviation is expected, since the force sensor used in this study measures only perpendicular force. As shown in Figure 3, there are two forces causing torque around the pivot point, which is the normal force) and Fs (shear force). Studies show that during a pedal stroke, shear force contributes approximately 25 % of the normal force to pedal power [6]. Based on this info, the deviation of the force sensor is accepted as reasonable.

VI. CONCLUSION

It is shown that under static loads, the force sensor gives accurate and precise measurements. For future work, a force sensor that can measure shear forces during a pedal stroke could be developed. In this study, a low-cost, affordable custom-made sensor was demonstrated to be successfully applied for simulating cycling activity, in a biomechanical simulation program to provide realistic results, while simulating environmental interactions.

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