Development of a portable microcontroller-based start block performance analysis device for sprint athletes

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Abstract

The start phase is a crucial techniques in sprinting. A good start is characterized by an extraordinary force exerted in the horizontal direction. This study develops a start block that can read a three-axis force and a practical device to monitor the sprint start technique based on the force exerted by the feet and block time at the start. The foot pedals obtain feet pushing forces at the start block. These foot pedals are equipped with load cell sensors that record forces in the X (front–back), Y (right–left), and Z (up–down) axes. The start block processes the sensor readings using a microcontroller. The data can be viewed using a smartphone or other mobile devices. The block time is calculated by analyzing the output force reading on the start block. Load Cell testing and calibration were performed for the two load cells used. Measurement results showed a very good linear correlation (>0.99). This linearity indicates that the system can properly measure the load for the tested range. To test the device, A total of 6 elite-level athletes performed two maximum sprints over a distance of 10 m during two separate testing sessions. Intraclass correlation coefficients were used to determine each parameter's reliability. The device showed high reliability ($p > 0.5$) on the Lx, Lz, Rx, and Rz axes, while the Ly and Ry axes had relatively moderate reliability. This result shows that the Lx, Lz, Rx, and Rz axes gave reliable measurements during the two separate testing sessions. In addition, the device produced accurate data readings, which correlated well with sprint performance. Thus, the developed device is suitable for biomechanical analysis of sprinting starts.

Key Words: - Microcontroller, Starting Block Performance, Sprinting

Introduction

The start phase is an integral part of sprinting. Because acceleration depends on force and power, knowing the force when exiting the start block is essential in predicting sprint performance (Murphy et al., 2003). Previous studies have shown that superior sprinters can better optimize force distribution by producing greater force against the start block (Čoh et al., 2017)(Behrens & Simonson, 2011). Furthermore, superior sprinters can quickly apply this force, allowing them to leave the starting block faster (Willwacher et al., 2013). In addition to the athlete's capability, the start block settings (e.g., distance between the blocks, distance between the starting line and front block, and slope) can also affect the start performance (Shinohara & Maeda, 2011). Thus, measuring the performance of athletes when exiting the start phase is essential for evaluating the performance of sprinters.

Previous studies have developed various methods and devices to improve starting performance (E D Lemaire, 1990)(Pain & Hibbs, 2007)(Delalija & Babić, 2008)(Haugen & Buchheit, 2016)(Musalem, 2016)(Wibowo et al., 2017)(Rudolf & Triyanti, 2020) (Gleadhill et al., 2020). The developed devices indicate critical characteristics to improve starting performance. For example, an efficient starting technique provides a quick reaction time on exit. As a result, elite-level athletes have better reaction time than sub-elite athletes (Fortier et al., 2005b). The same is true for force–time. Force–time is a measure of the force exerted over time. For example, based on the best time achieved in the 100 m events, athletes with better time records have better force–time than slower athletes (Willwacher et al., 2013). However, the ability of coaches to provide feedback to athletes is limited by the lack of measurement data that can support the process of providing feedback. Therefore, a measuring instrument is needed to provide details of the force produced and the athlete's block time in actual field conditions to provide more detailed, fast, and practical input. Although recorded footage may reveal biomechanical information that is essential to start a movement (i.e., foot pedal position, foot pedal angle, body position and posture at the set and go, speed, and acceleration), measurements of the launch force and time are

difficult to perform (Harland & Steele, 1997). Furthermore, previously devices that are to be applied in coaching to enhance start technique were frequently extremely expensive or impractical for field training (Cavedon et al., 2019)(Sandamas et al., 2019). Therefore, most sprinting coaches have not adopted the technology that can comprehensively analyze starting techniques. To overcome this information gap, in this study, a device with integrated load cells in the start block was developed to quantify the repulsive force of the athlete's foot as a function of time. While force data itself is crucial, as stated previously, it is also essential to keep in mind the practical implication and use of this information. Previous studies indicate that to improve start performance, impulse needed to be maximized (Payne & Blader, 1971) (Fortier et al., 2005a). Impulse is the integration of force against time from when the foot starts pushing the block until the foot leaves the block. It was also known that the starting performance seen from the velocity and acceleration of the sprint was influenced by the distance between foot pedals (Shinohara & Maeda, 2011) and the pedal angle (Guissard et al., 1992). This may also be related to impulse since the placement and pedal angle affect the position of the muscles and their capacity to transmit power to the start block. (Guissard et al., 1992)(Stock, 1962). It was fair to assume that the arrangement of the start block influenced the athletes' impulse, which determined start performance. Therefore, it was reasonable to conclude that the configuration of the start block affected the impulse generated by the athletes, which in turn determined start performance. As a result, collecting force measurements may be a quantitative strategy of adjusting the athlete's technique and start block configuration to the athlete's demands in order to significantly maximize their start performance.

Block time characterizes good start performance. Block time is also related to impulse; impulse is calculated after the foot started to push. In this study, block time is defined as the period between the stimulus sign of "go" until the impulse starts. Thus, it is reasonable to assume that block time must be minimized to get the best sprinting performance. However, in previous studies, the correlation between block time and overall sprint time is significant for the 100 m hurdle, 110 m hurdle, and 100 m but not for the other sprint events (Delalija & Babić, 2008). It was also clear that the implementation of reaction time measuring devices for athlete training remained quite limited. As a consequence, block time was not the primary outcome of this study. However, the output of the device developed in this study can be analyzed to obtain block time results to supplement force data.

Therefore, the device to help coaches monitor the aspects of start performance has been developed. The start block was designed with two-foot pedals equipped with three-axis (front-back, right-left, and top-bottom directions; Cartesian X, Y, and Z, respectively) load cells to measure the athlete's foot repulsion. Following the study's emphasis on training, the device was designed to prioritize practicality. The primary goal of this study was to develop a device that could be utilized to provide valuable feedback regarding the athlete's starting technique.

Material & methods

Mechanical Design

The device's mechanical design was based on the IAAF competition regulations (International Association of Athletics Federations, 2019). The developed device was constructed from 3 main components, i.e., the footplates, rail section, and sensor assembly, which housed the force gauge, as shown in Figure 1. To further ensure that the device complied with the rules and was of familiar design to practitioners, measurements for the device were based on the referenced starting block, i.e., the "Viking" model made by Nordic Sport. Furthermore, based on the previous studies, the following criteria were followed. The device could withstand a load of 1.5 kN (approximately the maximum load of repulsion of the athlete on one leg) (Čoh et al., 2017), without significant deflection (rigid) and had a 3-axis force measuring device in the form of a load cell.

The design was made in SolidWorks, and an initial simulation stage was performed. As required, the foot pedals were adjustable forward and backward along the notched rail and had an adjustable slope angle. The foot pedals were locked to the rail using quick-release bolts so that they could be easily adjusted. The load cell sensor used to measure the force was located under the foot pedals, connected using four bolts. The prototype start block was almost entirely made of sturdy steel. The foot pedals were lined with synthetic rubber on the final prototype for comfort and compatibility with cleats. As shown in Figure 2, the foot pedal unit was made so that the force exerted by the feet when pushing the start block could be read accurately. Under the sensor was a mounting such that the sensor remained well anchored during use and provided a linked site for quick release bolts, which locked the foot pedals to the rail.

Fig. 1. Device components of the start block force plate. 1) foot pedal unit, 2) rail, 3) sensor

Note :

1. LC lower plate	8. Bushing
2. LC	9. M8 Nut
3. LC upper plate	10. Head QR
4. support plate	11. pin QR
5. support frame	12. Cap QR
6. plate	13. pin
7. M8 Bolt	

Fig. 2. Exploded view right footrest

Electrical Design

The most important decision regarding the electrical components of the device was sensor selection. Load cell is a type of sensor that transduces mechanical strain, indicating a force applied to an electric signal (voltage) (Dara, 2017). In a previous study, 12 subjects (Slovenian sprinter athletes) (age: 22.4 ± 3.4 years; height: 177.6 ± 6.9 cm; body mass: 74.9 ± 5.2 kg), who had at least six years of training and participated in 60, 100, or 200 m sprints (Čoh et al., 2017), produced a maximum force of 1.2 kN at the start block (Čoh et al., 2017), produced a maximum force of 1.2 kN at the start block. Considering these findings, a sensor with characteristics listed in Table 1 was chosen. The sensor was the ZM3D model made by Anhui Zhimin Electrical Technology Co., Ltd.

Table 1. Load cell specifications

Parameter	Value	Unit
Material	Alloy steel	-
Capacity (R.C.)	5000	N
Sensitivity X-axis	0.9	mV/V
Sensitivity Y-axis	0.9	mV/V
Sensitivity Z-axis	0.9	mV/V
Zero balance	1	±% of rated output
Input resistance X, Y-Axis	700±5	Ohm
Output resistance X, Y-Axis	700±5	Ohm
Input resistance Z-Axis	350±5	Ohm
Output resistance Z-Axis	350±5	Ohm
Insulation resistance	5000	Mega-Ohm
Accuracy	1	±% of rated output
Non-linearity	0.1	±% of rated output
Hysteresis	0.1	±% of rated output
Temperature effect on min. dead load output	0.0026	±% of rated output/°C
Temperature effect on sensitivity	0.0015	±% of rated output/°C
Creep Error (30 minutes)	0.1	±% of rated output
Crosstalk from X to Y	1	±% of rated output
Crosstalk from Y to X	1	±% of rated output
Crosstalk from Z to X/Y	1	±% of rated output
Crosstalk from X/Y to Z	2	±% of rated output
Safe overload	150	±% of R.C.
Ultimate overload	200	±% of R.C.
Excitation, recommended	10.0	Vdc
Compensated temperature range	-10 to +40	°C
Operating temperature range	-20 to +60	°C

The load cell used was configured by the manufacturer using an independent full Wheatstone bridge design for all its axes; thus, the sensor's response was compensated for temperature and responded linearly to given load (within its operational range). To operate, the load cell requires a power supply to provide excitation voltage and a sensitive Analog to digital (ADC) to capture the generated signal.

To meet the excitation voltage requirements, a power supply was made from three 18650 Li-ion batteries arranged in series and connected to a 5 A battery management system (BMS) module. In addition, the battery pack was connected to a DC–DC step-down LM2596 regulator module to produce a constant voltage of 10 V.

ADC sampling, amplification, and conversion was performed by ADS1115 modules. The module used is a sigma-delta ADC with a 16-bit resolution. The module can sample data with a frequency of 250 kHz and can convert 8 to 860 samples per second (SPS). During testing and in the final prototype, the data was output by the

module with a frequency of approximately 45 Hz. At the highest amplification settings, this module can measure within ± 0.256 V with a resolution of $7.8125 \mu\text{V}$. The load cell configuration used resulted in the maximum force resolution of 4.34 N.

The ADS1115 conversion data were communicated via the I2C protocol for further processing by an ESP32-based microcontroller and displayed to the user. The chip used for the microcontroller was ESP-WROOM-32, which is a 32-bit microcontroller with a clock speed of up to 240 MHz and 512 kB memory. It also has serial communication, Bluetooth, and Wi-Fi capabilities built into the chip, which was important in this study. The microcontroller module used was ESP32 DEVKIT V1. Figure 3 shows the schematics of the electrical system.

Fig. 3. Signal processing circuit schematic

Results

Load Cell Testing and Calibration

Load cell is a component that transduces force as input into a change in voltage as an output. Therefore, calibration was critical in bridging the mechanical quantities of force and strain into electrical quantities of voltage (Dara, 2017). The load cell used in the device developed in this study measures forces in three axes, i.e., the longitudinal, latitudinal, and vertical axes (X, Y, and Z axes in the Cartesian coordinate system, respectively). Thus, each load cell had three whole Wheatstone bridges that must be measured and calibrated individually.

Fig. 4. Calibration using a universal testing machine

Load cell calibration was performed against known loads applied with a universal testing machine. The goal of this calibration test was to observe the accuracy of the sensor for the given loads and to find a correction factor so that the measured value matched the actual value (de Jesus et al., 2019). The test was performed for static loads of 100, 200, 400, 800, 1000, 1400, 1800, and 2000 N. The force generated by the universal testing machine may vary slightly from this value owing to the limitations of the test setup. A total of 100 samples were obtained by the electrical system, which was described in the previous section, and recorded on a laptop for each load. Figure 5 shows the testing and calibration configuration using the universal testing machine.

Linearity X Load Cell 1

Linearity X Load Cell 2

Linearity Y Load Cell 1

Linearity Y Load Cell 2

Linearity Z Load Cell 1

Linearity Z Load Cell 2

Fig. 5. Linearity of the X, Y, and Z axes of load cells 1 and 2

Measurements and calibrations were performed for the two load cells used. As specified, measurements were accurate to $\pm 1\%$ of rated output for loads above 10% of rated output, which meant that the measured value would normally fluctuate within ± 50 N around the average value. Figure 4 shows measurement results for the first load cell in the left column, followed by the second load cell data in the right column. It can be seen from the graphs that all measurement results showed a very good linear correlation. This was indicated by the value of R^2 coefficient being close to 1 (>0.99) in linear regression. This linearity indicates that the system can properly measure the load for the tested range. The gradient found from this regression between measured and actual load was used to correct the measured data.

Testing Prototype Device

After the load cell calibration was performed, the load cells were installed on the prototype start block. The final prototype implementation is shown in Figure 6b. The data generated by the device are the force magnitudes of the right foot pedal (R_x , R_y , and R_z) and of the left foot pedal (L_x , L_y , L_z) and the time of measurements relative to the start of measurement in milliseconds. Force data from the sensors are plotted as force magnitude in Newtons as a function of time. The displayed measurements were locally downloaded on a smartphone as a CSV file, which could then be examined and plotted in a graph using a spreadsheet processor.

To test the device, 6 elite-level sprinters were recruited (age: 21.6 ± 2.8 years; height: 174.5 ± 8.4 cm; weight: 63.5 ± 5.9 kg) with training experiences of 6.3 ± 1.2 years. Informed consent was obtained from all individuals included in this study.

The measurements were administered by two equipment technicians, one video officer, and one starter. Before the test, the athletes were explained the purpose of the measurement and were given 30 min to sufficiently warm up. Then, each athlete started twice using the prototype device, with approximately 10 min between measurements. Before the athlete started, the device was tared to ensure proper force measurement. The sprinters started after hearing the air horn “go” sound stimulus from a smartphone. Then, the sprinters ran as fast as they could for 20 m. The sprints were recorded by a Sony PJ4102 29 megapixel (16: 9) camera (Figures 6a and 6c show the perspective).

Fig. 6. Testing of the Prototype Device

The preliminary results of the device were force measurements on the left and right foot pedals. Figure 6 shows the measurement results for one of the foot pedals from one of the tests. For better readability, the graphs are plotted from the point when the “go” signal sounded to the moment after the feet left the pedals. Thus, observing the shape and amplitude of the graph provides insight into how the athlete pushed on the start block over time. For example, it can be discerned that the athlete, whose data is shown in Figure 7, initially quickly pushed with his right foot, then pushed steadily with his left foot before pushing explosively as he completely left the block.

From this primary data, the peak force, reaction time, and impulse were calculated. The peak force was taken as the momentary maximum force on the axis generated by the push of the foot on the start block. The reaction time was calculated from the time between the sound of the stimulus until the detection of significant repulsion (the start of launch) in the X, Y, or Z-axes. Finally, the impulse was calculated by integrating the force as a function of time using the trapezoid rule from the initial push until both feet were lifted from the pedals. For the purpose of calculation and analysis, negative values of impulse are considered errors and are replaced by 0. Table 2 shows the summary of averages of the test data and their standard deviation. Then, the data obtained from the first and second administrations were tested using Pearson correlation to check for test–retest reliability (Walsh et al., 2006).

Fig. 7. Sample left foot pedal data.

Axes Lx, Ly, and Lz and Rx, Ry, and Rz showed pushing forces towards the front–back, right–left, and up–down on the left and right foot pedal, respectively. Based on the Pearson correlation values for peak force and impulse in Table 2, the device showed high reliability ($p > 0.5$) in the Lx, Lz, Rx, and Rz axes, while axes Ly and Ry had relatively moderate to low reliability. This result shows that axes Lx, Lz, Rx, and Rz can give reliable measurements between the two administrations. In addition, the reaction time measurement results showed high reliability ($p < 0.5$).

Table 2. Sensor data and Test-retest reliability (n= 6)

Data	1 st Test Mean	1 st Test SD	2 nd Test Mean	2 nd Test SD	p-value
Peak Force Lx	514.0 N	177.5 N	528.7 N	156.4 N	0.9698
Peak Force Ly	55.7 N	26.9 N	43.0 N	11.7 N	0.6547
Peak Force Lz	369.7 N	124.9 N	421.9 N	144.2 N	0.8963
Peak Force Rx	118.0 N	163.9 N	131.3 N	139.5 N	0.9252
Peak Force Ry	42.8 N	58.0 N	42.8 N	23.8 N	0.2924
Peak Force Rz	345.8 N	114.2 N	328.3 N	116.6 N	0.9637
Impulse Lx	91.26 N·s	26.44 N·s	96.94 N·s	26.81 N·s	0.9303
Impulse Ly	1.20 N·s	1.70 N·s	0.25 N·s	0.62 N·s	-0.1705
Impulse Lz	58.59 N·s	22.46 N·s	73.66 N·s	22.13 N·s	0.9242
Impulse Rx	13.98 N·s	19.12 N·s	20.44 N·s	29.64 N·s	0.9899
Impulse Ry	2.20 N·s	1.98 N·s	2.44 N·s	3.02 N·s	0.6940
Impulse Rz	40.21 N·s	33.76 N·s	40.19 N·s	38.89 N·s	0.9955
Block Time	600 ms	55 ms	614 ms	46 ms	0.820

After determining which data are reliable, further insights can be obtained when sensor data are compared with data obtained by the video camera. From the footage, 5 m and 10 m speeds were calculated (distance traveled divided by the time taken to reach the distance) for each test. A Pearson correlation test was performed for the 5 m and 10 m speed versus peak Lx (PLx), Lz (PLz), Rx (PRx), Rz (PRz) force, total impulse in the X-axis (IMPx), and magnitude of resultant impulse in the X and Z-axes (IMPRxz). The results are shown in Table 3. IMPx was calculated by summing the X-axis impulse on the right and left pedals, while IMPRxz was calculated by summing the X- and Z-axis impulses as follows.

$$IMPRxz = \sqrt{(Impulse Lx + Impulse Rx)^2 + (Impulse Lz + Impulse Rz)^2}$$

Table 3. Pearson Correlation for averaged sensor data against 5m and 10m speeds (n=6)

Data (Averaged)	Peak Lx	Peak Lz	Peak Rx	Peak Rz	IMPx	IMPRxz
5m Velocity	0.79	0.77	0.42	0.60	0.91	0.84
10m Velocity	0.95	0.82	0.72	0.87	0.90	0.92

Table 3 shows the new Pearson correlation coefficients for averaged IMPx and IMPRxz versus 5 m and 10 m velocity. The Pearson correlation values in the table clearly show that sensor readings can predict sprint performance in the early acceleration phase very well. These tests show that the data generated from the sensor strongly correlate ($p > 0.5$) with sprint performance (indicated by speed). The performed measurements show that athletes with higher peak forces and total impulse are likely to be faster. The averaged data showed that the most relevant variable for speed was IMPx, IMPRxz, and Peak Lx. Of note, left foot is the leading foot used by most athletes in the test, which affects which data (between the left and right foot pedals) are more relevant for peak forces. IMPx and IMPRxz do not have this left-right footedness problem because the left and right foot pedal data are summed. The obtained results show that athletes and coaches can use these data to improve sprinting speed and start technique by giving quantitative feedback on what modifications increase peak force and impulse. These measurements can also provide data on what the athletes can improve and how much they have improved between tests.

Dicussion

Upon review of primary sensor data, it was revealed that the data contained errors due to jitter and bias. As discussed in subsection 2.3, jitter occurred primarily when the load imposed on the axis was below or around 1% of the rated capacity (around 50N) but could also result from the sensor's precision of $\pm 1\%$ rated capacity (50N). In addition, the athlete's movement caused bias as they adjusted their posture. The average of 12 samples before the initial push for each axis was subtracted after that to mitigate this bias. On further development of this type of device, better solutions to this issue, such as implementing a high pass filter and other de-noising techniques, are highly advised.

The reason for the low reliability of the Y-axis in both foot pedals could be observed in Figures 7a and 7b, where the Y-axis force reading was unstable. As previously observed, the jitter resulted from low loading conditions on the axes and the accuracy of the load cell in that measurement range since the athlete's body weight and pushing force primarily loaded the X and Z axes. The mean maximum readings of L_y and R_y were small relative to the others (55.67 N and 42.78 on the first administration, respectively), which was also consistent with the jitter found during sensor calibration and testing. It could also be observed in Figures 7a and 7b that after the athlete has left the block (and therefore no load is imposed on the block), the other axes also begin to fluctuate.

The reaction time measurement was showed high reliability. The reaction time is close to what is found in the references (Delalija & Babić, 2008). The sensor readings could predict sprint performance in the early acceleration phase very well. The tests showed that the data generated from the sensor did correlate strongly ($p > 0.5$) with sprint performance (indicated by speed). The measurements showed that athletes with higher peak forces and total impulse are likely to be faster, consistent with previous research (Willwacher et al., 2013). The averaged data showed that the most relevant variable to speed was IMP_x , IMP_{xz} , and $Peak L_x$. It should be noted that the left foot is the leading foot used by most of the athletes in the test, which affects which data (between the left and right foot pedals) are more relevant for peak forces. IMP_x and IMP_{xz} do not have this left-right footedness problem since the left and right foot pedal data are summed.

With these results, it could be concluded that athletes and coaches could use the data to improve sprinting speed and start the technique by giving quantitative feedback on what modifications increased their peak force and impulse. It can also provide data on where the athlete can improve and how much they have improved between tests. As is, when compared with previous studies, this research provided improvements in terms of effectiveness and ease of use (Rudolf & Triyanti, 2020)(Iyer & Brennan, 2016)(Shinohara & Maeda, 2011)(E D Lemaire, 1990). The prototype device developed was able to be applied efficiently because it could be used with a mobile device while maintaining quick and accurate readings. In addition, the prototype device developed had advantages in terms of affordability. It is meant that practitioners could use the finalized device prototyped in this study in the future to evaluate sprinter athletes during training.

Conclusions

Overall, the reliability simulation and experimental results show that the developed prototype start block analysis device can measure and evaluate start performance. The athletes participating in this study demonstrated variations in performance between the first and second tests during performance testing. This was normal because athletes' responses to stimuli differed depending on the athlete and environmental conditions. A more extensive test with more administered tests and participants is recommended to properly assess the device's accuracy.

Conflicts of interest

The authors declare no conflict of interest.

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