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3D BIOMECHANICAL ANALYSIS OF SWIMMING START MOVEMENTS USING A PORTABLE SMART PLATFORM WITH ANDROID PIE

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Abstract

The purpose of this study was to analyse the kinetic and kinematic parameters of starting movements in swimming using a portable smart platform with Android pie for sport biomechanics applications. A TAL220 load cell sensor, microcontroller, an Arduino Nano, Wi-Fi module, and Bluetooth HC-05 were used to support the various components of the prototype product. The sample of this study comprised 46 university students, i.e., 26 males (average age: 19.2 ± 0.8 years old, height: 167.97 ± 6.09 cm, weight: 59.40 ± 7.61 kg) and 20 fameless (average age: 19.2 ± 0.8 years old, height: 161.97 ± 6.09 cm, weight: 55.40 ± 7.61 kg). The inter-observer suitability test for the measurement of 46 samples between prototype and commercial (KiSwim Force Platform 9691A) products for the reaction time, ground reaction force, and power variables showed no difference. These results indicate that the use of prototypes and commercial products has a high level of stability. The developed prototype product can be used as an alternative to measure the maximum leg power, reaction time, and ground reaction force when starting to swim; this product has the advantages of low cost, portability, and real-time data acquisition.

Keywords: Biomechanics, Force, Kinetics, Prototype product, Swimming.

1. Introduction

Mechanics is a branch of physics that studies movements and changes in materials caused by mechanical interference (i.e., applied force) [1, 2]. Meanwhile, biomechanics is defined as the combination of applied mechanics, biological sciences, and physiology [3]. The purpose of studying the application of biomechanics in sports science is to determine the basic scientific concepts applied in the form of human movement, in accordance with one's physical characteristics [4]. Meanwhile, in science, sports biomechanics studies mechanical laws and structures of the locomotor system of a moving body related to its strength or assisted by gravity. There is a concurrent advancement in sporting technology owing to the collaboration between talents possessed by athletes and the application of digital technology, which accelerates the attainment of sporting achievements [5-7].

Furthermore, sports technology helps coaches to analyse the performance of athletes, improves the quality of training programs, allows them accurately measure time, helps referees or judges make faster decisions on violations, and helps the sports equipment and clothing industry develop effective and efficient designs. This is evidenced by the use of Global Positioning System (GPS) and micro sensor technology to produce data such as measurement of speed, mileage, acceleration, number of calories expended, and athlete's movement patterns [8-11]. Another research stated that humans move mechanically owing to the interaction of a number of ground reaction forces produced by the body and nature such as muscle activity and gravity or air resistance [12].

Mechanical power is the mechanical principle of the rate at which the athlete does work or transfers energy to complete a movement task. A mechanical power balance analysis can provide valuable insight into the capability of athletes to generate power and also into technique factors that affect the effective use of power for performance. In terms of the mechanism of body movement, especially when exercising, the measurement of leg power, reaction time, and ground reaction force is very important because these physical components support the overall body movement and help improve athlete performance. Leg power and ground reaction force are some of the kinetic components that are needed for body movements because most motions involve the lower body, especially the legs. Leg power functions help to support the overall body weight, maintain body balance, and produce stable strength. The results of the study conducted by Mooney et al. [13] show that there is a significant relationship between leg power and 10-meter sprint acceleration. Therefore, the higher is the generated leg power, the greater the speed. These results agree with those obtained in the studies on swimming starts, which show that the stronger are the leg repulsions, the higher is the produced body momentum.

The leg power generated during the repulsion considerably affects the reaction time produced by the mechanism of motion, which is the origin of the stimulus response to start a movement when the stimulus is provided [14, 15]. A swimmer initiates motion by quickly and strongly pushing their feet at the start block as soon as the signal sounds [16]. The results of the study showed that when the swim start was efficiently performed, proper technique contributed 25, 10, and 5% to the total time for the distances of 25, 50, and 100 m, respectively. To study this process, the measurement tools for the leg power, reaction time, and ground forces are developed using a ground reaction force platform, which is placed on the surface of the start beam. The measuring instrument was first used in 1895 by Marey from France. This system used a gas-filled tube that was capable of measuring the pressure and ground reaction force of a runner's foot on the surface of repulsion [17-19]. Furthermore, in 1916, Amar [20] developed the same tool, which measured the strength sensitivity of the platform to achieve vertical and horizontal force reactions [21-23].

In 1938, Elftman [24] succeeded in developing a ground reaction force platform that used a spring to calculate the forward and backward forces of the runner's feet during maximum repulsion. This tool has limitations in terms of the displacement of spring pressure and lower frequency [1, 3, 25]. A modern ground reaction force platform relies on electronic components (e.g., a strain gauge or a piezo electric system) and was first developed by the Kistler company in 1964. This type of platform is effective; it has a high natural frequency and record the ground reaction force data precisely, quickly, and accurately. Therefore, in 1969, the company for the first time produced and marketed a measuring instrument, which conformed to an international standard; this instrument was called the 3D ground reaction force platform and was used by the sports technology industry worldwide. In 1976, the Advanced Mechanical Technology Incorporated (AMTI, USA) company, in collaboration with the Kistler company, introduced a new product that had a larger surface voltage platform and was less expensive. The Omega Company tried to produce the latest start block, OSB11, by collaborating with Kistler; they used type 9260A and type 9017B ground reaction force transducers. These components are used to measure horizontal, vertical, and horizontal take-off velocities as well as the reaction time of the peak ground reaction force. This measurement tool was first used in 2010, at the Commonwealth Games swimming championship in Delhi. Because there is a need to measure leg power, reaction time, and ground force in swimming sports, it is necessary to develop a portable measuring instrument according to the characteristics of the performed movement to quickly acquire precise and accurate data.

2. Methods

2.1. Research methods

This study uses a research and development (R&D) approach. Ellis and Levy [26] stated that R&D results include the development of new tools, products, and processes through problem identification, literature study, design and development, testing, evaluation, and analysis of results.

2.2. Participants

The sample of this study were 46 university students, i.e., 26 males (average age: 19.2 ± 0.8 years old, height: 167.97 ± 6.09 cm, weight: 59.40 ± 7.61 kg) and 20 females (average age: 19.2 ± 0.8 years old, height: 161.97 ± 6.09 cm, weight: 55.40 ± 7.61 kg). The instruments used in this study included two high resolution Handycam cameras (Sony HXR-MC2500, Japan), a high-speed camera (Fastec Imaging TS5-H, USA), a 3D force platform (The AMTI Optima Series 20210, USA), and a motion capture system software (Frame DIAZ IV, Japan).

2.3. Statistical analysis

The reliability test of prototype and commercial products uses the intraclass correlation coefficient test and the Bland-Altman approach. Bland-Altman plot is a statistical method, which is used to compare two measurement techniques. This test is used to determine the relationship between the difference and average in addition to identifying the outliers.

The measuring instrument tested had adequate stability if interclass correlation coefficient (ICC) value between measurements was > 0.50 and high stability if the ICC value between measurements was ≥ 0.80 [27, 28]. To determine the two differences in the average starting performance between men and women, the paired *t*-test was used.

2.4. Clarification of terms of kinematics parameters when starting the movement

The limitation of movement parameters at start is determined to facilitate the analysis process of calculating swimmer's mechanics. The parameters include the block time, flight time, flight distance, total time, total distance, vertical displacement of center of mass (CoM) at take-off, horizontal vertical displacement of CoM at entry, height of take-off, height of entry, vertical displacement of CoM at take-off, horizontal velocity of CoM at take-off, vertical velocity of CoM at take-off, horizontal velocity of CoM at entry, horizontal displacement of CoM at take-off, vertical velocity of CoM at entry, angle of entry, leg power (watts/kg), and ground reaction force; these parameters are shown in Table 1 and Fig. 1.

Table 1. Definition of kinematics parameters during the start motion.

Parameter Analysis	Definition
Block time (s)	Recorded time from the start signal to the take-off from the starting block
Flight time (s)	Duration of time in the air when the foot is repulsed and leaves the start block until the hand touches the surface of the water
Flight distance (m)	Distance travelled from the location where the repulsed foot leaves the start block until the hand touches the surface of the water
Total time (s)	Duration of time from the start of the movement until the hand touches the surface of the water
Total distance (m)	Distance travelled from the start of the movement until the hand touches the surface of the water
Horizontal displacement of CoM at entry (m)	Horizontal CoM displacement from the start of the movement until the hand touches the surface of the water
Horizontal displacement of CoM at take-off (m)	Horizontal CoM displacement from the start of the movement when the last repulsed leg leaves the start block surface
Vertical displacement of CoM at entry (m)	Vertical body CoM displacement from the start of the movement until the hand touches the surface of the water
Vertical displacement of CoM at take-off (m)	Vertical body CoM displacement from the start of the movement when the last repulsed leg leaves the start block surface
Height of take-off (m)	Height of the body CoM at the take-off phase
Height of entry (m)	Height of the body CoM at the entry phase
Horizontal velocity of CoM at take-off (m/s)	Horizontal velocity of body CoM when the last repulsed leg leaves the start block surface

Vertical velocity of CoM at take-off (m/s)	Horizontal velocity of the body CoM when the last repulsion leg leaves from the start block
Horizontal velocity of the CoM at entry (m/s)	Horizontal velocity of body CoM when the hand touches the surface of the water
Vertical velocity of CoM at entry (m/s)	Vertical velocity of body CoM when the hand touches the surface of the water
Angle of entry (º)	Angle of body CoM at the entry phase
Leg power (watts/kg)	Ability to quickly exert force with lower extremities
Ground reaction force (N)	Equal in magnitude and opposite in direction to the force that the body exerts on the supporting surface through the foot

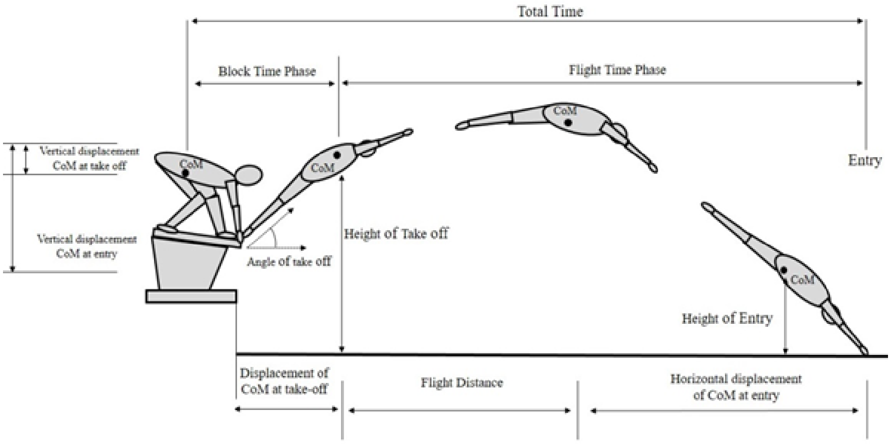

Fig. 1. Testing of prototype products when performing track start techniques.

3. Test of Prototype Products

Figure 2 shows that during the prototype product testing, each swimmer was allowed to start the movements eight times in rotation; the track length was 25 m. The repulsion results (in the form of leg power, ground reacting force, and reaction time) during the start of the movements were automatically calculated in real-time via the Swim Force application on a smartphone.

Fig. 2. Testing of prototype products when performing track start techniques.

3.1. Materials

Figure 3 shows a prototype product, which is designed to measure leg power, reaction, and ground reaction force. The electronic components used are described below.

3.1.1. Load cell sensor

The TAL220 load cell sensor is a component that is capable of measuring up to 200 kg of load. Load cell is a sensor that converts force into an electrical signal in the form of voltage, current, or frequency changes depending on the type of circuit used. When a load is applied to the sensor, it changes the voltage resistance, which causes the output to change the result of the applied voltage input. For general parallel plate capacitors, the capacity is directly proportional to the number of overlapping plates and dielectric between plates and inversely proportional to the gap.

3.1.2. Arduino nano

This component is an open-source electronic network board, which is based on an Atmega 328 microcontroller. The device is a chip or an integrated circuit that is capable of creating programs; therefore, the electronic circuit can read and process the input while producing the desired output.

3.1.3. Charger module

This module is a network board that charges the battery by utilizing a USB connection from the prototype measuring instrument to the power centre.

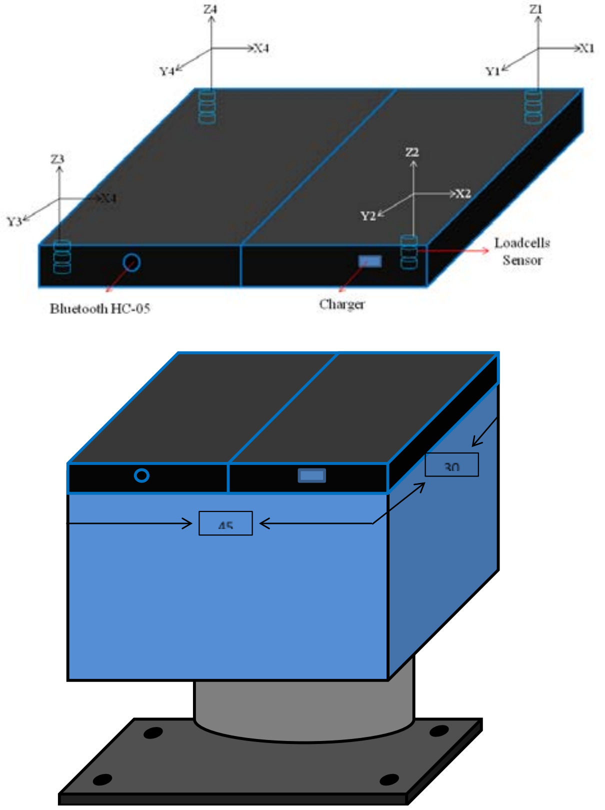

Fig. 3. Prototype product for measuring leg power, reaction time, and ground reaction force during the swimming start.

3.1.4. Bluetooth HC-05 module

This component is an easy-to-use serial port protocol Bluetooth module for wireless serial communication. HC-05 utilizes a 3-Mbps Bluetooth modulation V2.0 + EDR (enhanced data rate) using radio waves with a 2.4 GHz frequency. This module is used as a slave or a master with 2 configuration modes, i.e., AT and communication. The AT and communication modes allow to configure settings of the HC-05 and connect Bluetooth with other devices. HC-05 operates without a special driver to communicate between Bluetooth; the output signal distance capability is 30 m.

3.1.5. HX711 module

This is a weighing module, which converts measured resistance changes into voltage magnitudes through a series of electric current flows. This module communicates with a microcontroller component application via the TTL232 device.

3.2. Swim force software

The smartphone application program, named “Swim Force”, is used to read the results of the prototype measuring instrument (i.e., leg power, reaction time, and ground reaction force). In addition, the program reads the input, processes it, and produces a desired output using Arduino IDE and the Atmega328 microcontroller. The program communicates with the prototype product via the software contained in the Android application using a wireless system. In addition, the HC-05 module utilizes a 3-Mbps Bluetooth modulation V2.0 + EDR using radio waves with a 2.4 GHz frequency. HC-05 has 2 configuration modes, i.e., AT and communication modes. The AT mode is used to change the configuration settings of HC-05, Bluetooth, and other devices.

Figure 3 shows the prototype product, which is a rectangular solid metal base plate with the dimensions of 25 cm × 45 cm and 1-kg weight. It can measure the force of 10-5000 N with an accuracy level of less than two percent for the measurement range used. The program used to read the results of the prototype leg power measuring instrument, reaction time, and force is called swimming force testing, which is a software developed through the Inventor 2 application. The program is used to read inputs, process inputs, and produce an output using the Arduino IDE. For communication, the program from this prototype measuring instrument utilizes an android application, which uses a wireless system that is based on the Bluetooth HC-05 module circuit. HC-05 utilizes a 3-Mbps Bluetooth modulation V2.0 + EDR using 2.4-GHz frequency radio waves.

4. Results and Discussion

4.1. Prototype product analysis

The reliability test of prototype and commercial products uses the intraclass correlation coefficient test and Bland-Altman approach. Bland-Altman plot is a statistical method, which is used to compare two measurement techniques.

Table 2 shows the reaction time variable during the first, second, and third measurements; it was determined that the alpha coefficient value was very high, i.e., 0.984, 0.995, and 0.925, respectively. Furthermore, the ANOVA value shows that there was no significant difference between the prototype and commercial products i.e., 0.087, 0.071, and 0.074, respectively. For the ICC value, the results show that there was no difference in the assessment between the prototype and commercial products; the reliability between the test equipment was very high i.e., 0.996, 0.997, and 0.928, respectively. Thus, by analysing these data, it is determined that there is an agreement between the prototype and commercial products in analysing the reaction time at the swimming start.

Table 3 shows the ground reaction force variable during the first, second, and third measurements; it was determined that the alpha coefficient value was very high i.e., 0.987, 1.000, and 1.000, respectively. Furthermore, the ANOVA value shows that there was no significant difference between the prototype and commercial products i.e., 0.790, 0.984, and 0.889, respectively. For the ICC value, the results showed that there was no difference in the assessment between the prototype and commercial products, and the reliability between the test equipment was very high i.e., 0.927, 1.000, and 1.000, respectively. Thus, based on the results of these data it is concluded that there is an agreement between the prototype and commercial products when analysing the ground reaction force at the swimming start.

Table 2. Assessment of reaction time using the prototype and commercial products.

Assessment	Reaction Time (s)		
	Cronbach's alpha	ANOVA	ICC
1	0.984	0.087	0.996
2	0.995	0.071	0.997
3	0.925	0.074	0.928

Table 3. Assessment of ground reaction force using the prototype and commercial products.

Assessment	Ground Reaction Force (N)		
	Cronbach's alpha	ANOVA	ICC
1	0.987	0.790	0.927
2	1.000	0.984	1.000
3	1.000	0.889	1.000

Table 4 shows the ground reaction force variable during the first, second, and third measurements; it is determined that the alpha coefficient value is very high i.e., 0.980, 0.965, and 0.948, respectively. Furthermore, the ANOVA value showed that there was no significant difference between prototype and the commercial products i.e., 0.802, 0.180, and 0.815, respectively). For the ICC value, the results showed that there was no difference in the assessment between prototype and the commercial products, and the reliability between the test equipment was very high i.e., 1.000, 0.970, and 0.985, respectively. Thus, based on the results of these data, it is concluded that there is an agreement between the prototype and commercial products in analysing the power at the swimming start.

Figure 4 shows that the Bland-Altman plot has a range of scores between 81.7 and 74.9, with the bias of difference of 3.4.

Table 4. Assessment of force using the prototype and commercial products.

Assessment	Power (watts/kg)		
	Cronbach's alpha	ANOVA	ICC
1	0.980	0.802	1.000
2	0.965	0.180	0.970
3	0.948	0.815	0.985

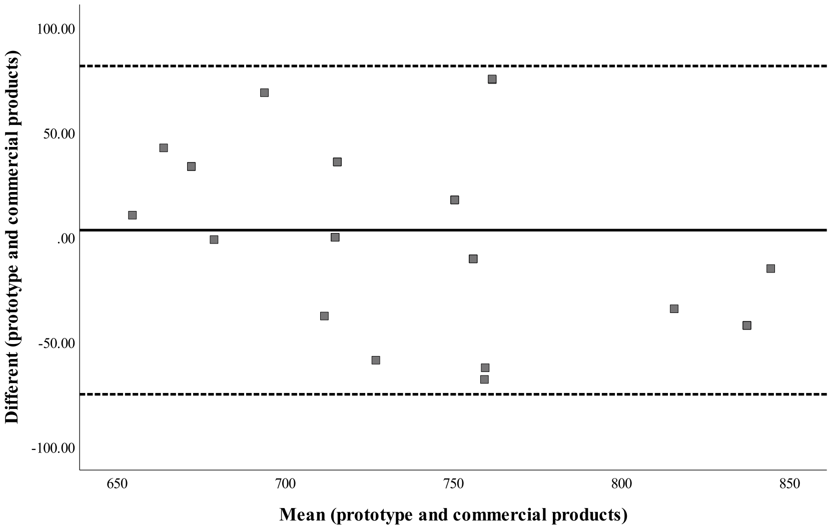

Fig. 4. Distribution of inter-observer suitability test data for leg power measurements.

Figure 5 shows that the Bland-Altman plot has a range of scores between 412.3 and 237.4, with the bias of difference of 87.5.

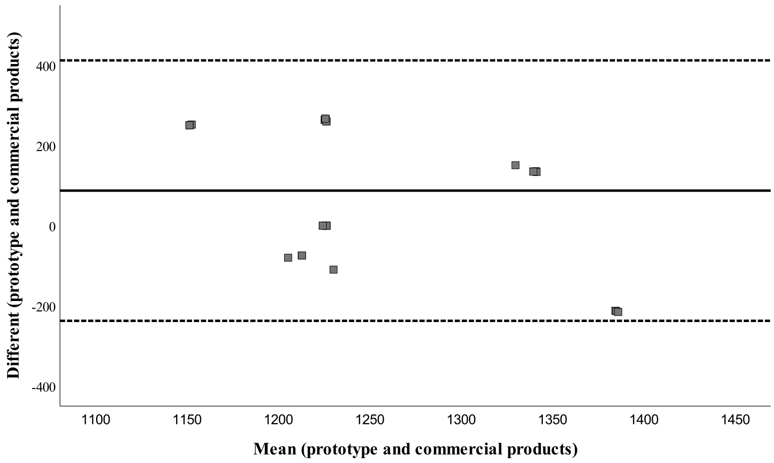

Fig. 5. Distribution of inter-observer suitability test data for ground reaction force measurements.

Figure 6 shows that the Bland-Altman plot has a range of scores between 0.42 and −0.21, with the bias of difference 0f 0.09. The results of inter and intra-observer tests using the Bland-Altman test method showed that there was a good agreement between the measurements. The inter-observer suitability test for the measurement of 46 samples between prototype and commercial products for the reaction time, force, and power variables showed no difference. These results indicate that the use of prototype and commercial products has a high level of stability.

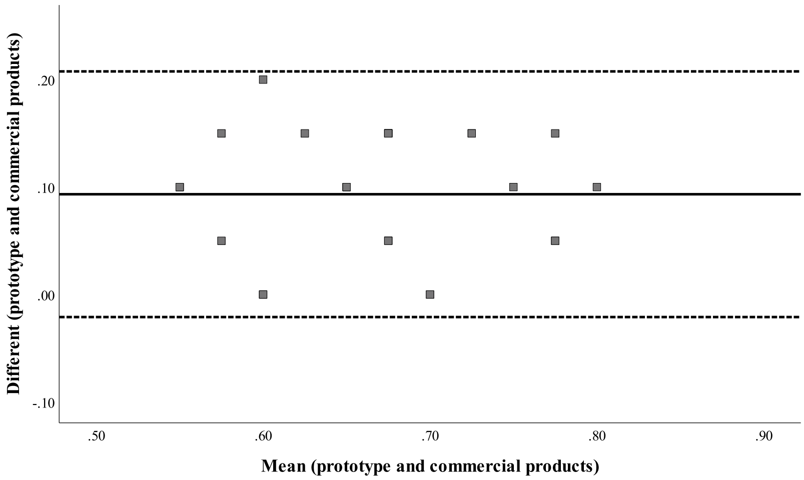

Fig. 6. Distribution of inter-observer suitability test data for reaction time measurements.

4.2. Swimming start analysis

Table 5 shows the results of data analysis of the mean values and standard deviations of male and female groups when performing start movement techniques in swimming. A total of 18 motion kinematics parameters were analysed, and significant differences were observed; the results of the male group were greater than those of the female group, especially for 6 parameters, i.e., flight time (p = 0.021), total time (p = 0.018), height of take-off (p = 0.008), vertical velocity of CoM at take-off (p = 0.038), leg power (0.042), and ground reaction force (0.036).

Table 5. Average value and standard deviation of the data processing results (mean ± SD).

Variable Analysis	Male	Female	Sig.
	Mean ± SD	Mean ± SD	
Block time (s)	0.68 ± 0.08	0.67 ± 0.08	0.542
Flight time (s)	0.37 ± 0.08	0.33 ± 0.07	0.021*
Flight distance (m)	2.85 ± 0.09	2.65 ± 0.09	0.087
Total time (s)	2.89 ± 0.18	2.21 ± 0.35	0.018*
Total distance (m)	0.99 ± 0.10	0.87 ± 0.13	0.095
Horizontal displacement of CoM at entry (m)	1.09 ± 0.21	1.08 ± 0.11	0.125
Horizontal displacement of CoM at take-off (m)	2.12 ± 0.56	1.96 ± 0.48	0.143

Vertical displacement of CoM at entry (m)	0.54 ± 0.09	0.63 ± 0.11	0.076
Vertical displacement of CoM at take-off (m)	0.89 ± 0.34	0.82 ± 0.28	0.242
Height of take-off (m)	1.45 ± 0.09	1.08 ± 0.08	0.008*
Height of entry (m)	0.71 ± 0.09	0.63 ± 0.09	0.123
Horizontal velocity of CoM at take-off (m/s)	3.32 ± 0.23	2.99 ± 0.51	0.089
Vertical velocity of CoM at take-off (m/s)	0.12 ± 0.64	0.64 ± 0.61	0.038*
Horizontal velocity of CoM at entry (m/s)	0.71 ± 0.07	0.64 ± 0.37	0.187
Vertical velocity of CoM at entry (m/s)	0.67 ± 0.08	0.62 ± 0.07	0.076
Angle of entry (deg.)	18.5 ± 1.15	17.5 ± 1.28	0.143
Leg power (watts/kg)	1545 ± 8.64	1325 ± 9.35	0.042*
Ground reaction force (N)	976 ± 6.52	742 ± 7.24	0.036*

4.3. Discussion

The time of the swimming race is affected by the starting, swimming time, turning, and finishing phases [29]. In 50 m and 100 m short range races, the maximum start ability is the main parameter for achieving the best record time [30]. The swimmer's fastest time to the distance of 15 m from the initial start jump can predict the swimmer's success in achieving the best time of the entire travel especially for short distances [31]. Some researchers define the start performance as the time interval from the beginning of the start signal to the swimmer's head reaching the surface of the water or by swimmers reaching the distance of 10 m or 15 m [32]. The results of other studies indicate that start contributes approximately 11% to the 50 m freestyle and 5% to the 100 m freestyle total swimmer's time record [33]. Therefore, to obtain the best time record, it is essential to increase the ability to start.

One of the factors that affected the jump distance at start is the take-off. To obtain a faster start, at the time of the take-off, the swimmer must quickly move CoM to the front, to maximize the force acting on both legs towards the back and maximize the force acting on both hands towards the start block in the forward direction [34]. In addition, according to Barlow et al. [31], the reaction time, vertical and horizontal leg force applied to the starting block, and low body resistance during sliding under water are essential factors that determine the success of the start. In addition, several studies have determined that the peak horizontal force [15], peak vertical force [35], resultant take-off velocity [33], horizontal take-off velocity and take-off angle [19], block time, movement time, vertical impulse horizontal impulse [36], average horizontal acceleration, and peak horizontal acceleration [29] are the main supporting indicators for achieving maximum performance when a swimmer starts moving. The slope of the body between 40° and 45° will produce the maximum time in air and further increase the horizontal velocity of the body [32].

Currently, the start techniques that are frequently used in swimming are the grab start and track start, which are both rear and front weighted techniques [19]. These techniques have advantages and disadvantages depending on the characteristics of the match number and the ability of swimmers. The main difference between the two start techniques is the position of the feet on the start block board. For the grab start technique, the two feet are positioned parallel to the front of the start block with the toes pressed firmly on the front edge of the start block's surface. Swimmers must quickly react and move weight forward after the start signal, and body position and legs should be aligned so that maximum strength can be distributed by pushing on the start block [37]. For the track start position one foot is placed in front with the toes pressed firmly on the front of the start block board, while the other foot is on the back of the start block [34]. This track start technique has the advantage of a faster initial reaction time so that the travel time is shorter, and the position of swimmer's CoM is leaning backward from the start block board, which increases swimmer's impulses by generating momentum for the body to jump farther [38]. The track start technique produces longer jump distance compared to the grab start technique [37]. This is attributed to the contribution of both legs, which alternately press the starting block to produce the maximum horizontal speed, and strength of both hands that pull the body just before sliding into air [2].

There is still a lack of scientific information related to the analysis of three-dimensional motion in the studies on kinematics parameter variables regarding the start analysis in swimming, especially in Indonesia. Thus, it is essential to conduct a study to compare the performance in male and female groups. Flight distance has a significant relationship with the height of take-off during the take-off phase. This result indicates that the distance the swimmer travels at the start is affected by the contribution of the movement momentum at the height of take-off; specifically, the greater is the power of take-off, the greater is the distance achieved by the swimmer. Another parameter that has a significant correlation value is the horizontal velocity of CoM at take-off and the total time. This result indicates that the total time of the track start motion is affected by the horizontal velocity factor of CoM during the repulsion of both feet and hands.

The success of the swimming start technique is affected by several parameters of motion kinematics indicators including the flight distance, horizontal velocity of CoM at take-off, vertical displacement of CoM at take-off, leg power and force; leg power and force just before the take-off are the factors that affect the success of the start performance in swimming. In addition, leg repulsion and maximum pulling of both hands on the start block board increase the horizontal body speed, which results in a longer jump distance. The results of this study agree with those in García-Ramos et al. [2]; specifically, it is determined that the force of CoM at take-off is one of the kinematics parameters of motion that considerably contributes to the maximum jump results at the start. The differences in motion kinematics in the male group especially in term of mechanic leg power and force are greater than those in the female group. These results indicate that leg power and force are essential for repulsion when performing track start techniques in swimming. By repulsing feet alternately to each other and pulling up with both hands on the starting block board, it is possible to increase the horizontal velocity of body, which produces a longer jump. The results of this study agree with those in García-Ramos et al. [2]; specifically, the force of CoM at take-off is one of the kinematics parameters of motion that considerably contributes to the maximum jump results at the start.

5. Conclusion

In conclusion, the developed prototype measuring product can be used as an alternative instrument to measure leg power, reaction time, and ground forces at the start and at the end of a swimming session. The advantages of the developed prototype product are that it can be used with a smartphone to produce real-time data and its low cost because it is made from local components.

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