Wearable System for Measuring Impact Force and Response Time in Taekwondo Using Piezoresistive Sensors

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Keywords: Impact Force, Piezoresistive Sensors, Response Time, Taekwondo, Wearable Devices.

Abstract: This paper presents the design and preliminary validation of a wearable prototype integrated into a Taekwondo chest protector. The system combines piezoresistive force sensors and visual LED stimuli to measure two critical performance parameters: impact force and response time. Unlike traditional measurement systems that are limited to laboratory settings, the proposed device enables real-time assessment in realistic training environments. The sensors were calibrated using a progressive load method, and a linear model without intercept was selected to ensure proportional accuracy. Six athletes participated in the experimental protocol, executing the Bandal Chagui technique under sequential and random visual conditions. Results showed a decrease in impact force and an increase in response time under the random condition, suggesting that cognitive load affects technical performance. The system proved to be portable, low-cost, and suitable for integration into regular training routines.

1 INTRODUCTION

The application of wearables in sports is a promising area and presenting substantial advantages in performance analysis and injury prediction (Seçkin et al., 2023). Wearable technology has the potential to revolutionize sports and exercise science thanks to its ability to transmit numerous types of data in real time to support training processes, and can also be applied to assess well-being, health, longevity, and disease (James et al., 2024).

Instrumental devices used in sports may employ force or inertial sensors and biosignals acquisition systems in order to capture impact force, reaction/execution time, velocity, power, and accuracy during activities such as kicking. These parameters are important in disciplines such as Taekwondo that demands not only technical skill but also a high level of power and speed to be effective in competitive situations. Also, training systems focused on measuring sliding and kicking parameters with data visualization include embedded systems based on microcontrollers and wireless data transfer (Vásquez et al., 2023).

Response time is defined as the interval between the onset of a visual, auditory, or human stimulus and the moment the action or movement reaches the target (Sant'Ana et al., 2017). Impact force is a key parameter in combat sports, it reflects the athlete's ability to generate effective power during the execution of a technique. Various technological methods exist to quantify this variable.

Examples of system developments for monitoring these parameters include Sant'Ana et al. (2017) that evaluated the effects of fatigue on reaction time, response time, and impact force during the execution of a roundhouse kick (Bandal Chagui). Their methodology combined surface electromyography (EMG) and triaxial accelerometry sensors placed on the athlete's ankle, enabling detection of both muscle activation onset and impact moment. A visual stimulus was used to initiate the movement; thus, reaction time was measured from the onset of the stimulus to muscle activation, and response time was measured until the movement reached the target. Similarly, Ervilha et al.

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Chato-Cantos, E. N., Rivera-Zamora, J. J., Villa-Parra, A. C., Cevallos-Larrea, P. and Alvarez-Alvarez, M.
Wearable System for Measuring Impact Force and Response Time in Taekwondo Using Piezoresistive Sensors.
DOI: 10.5220/0013717400003988

In *Proceedings of the 13th International Conference on Sport Sciences Research and Technology Support (icSPORTS 2025)*, pages 200-207
ISBN: 978-989-758-771-9; ISSN: 2184-3201

(2020) proposed a more detailed evaluation methodology by fractionating reaction time into three components: pre-motor time, response time, and movement time. Their study compared elite and novice athletes, using surface EMG on trunk and lower limb muscles, along with an electrogoniometer to measure the knee angle during the kick. The electrogoniometer helped identify the start of the movement, while a switch placed on the target marked the end. The study of Mudric et al. (2015) proposed a method based on life-size projected videos simulating specific combat scenarios. Here, karate athletes responded to visual stimuli showing real offensive techniques recorded from the opponent's perspective. Participants were required to perform a specific defensive action, which was detected using 3D kinematic analysis through an infrared camera system and reflective markers.

In this regard, studies have shown that test validity improves when human or context-specific stimuli are used, as they elicit more natural and representative responses of actual sports performance (Paul et al., 2016). This does not dismiss visual or auditory stimuli, which also demonstrate high reliability, but adapting the evaluation method to a contextualized environment proves more suitable for distinguishing between skill levels. For example, integrating technology into mobile elements that simulate specific combat situations may provide more representative and useful assessments for training design. Falco et al. (2009) developed a system to measure both impact force and execution time of the Bandal Chagui kick in Taekwondo. They integrated a force platform into a dummy composed of two circular wooden plates, equipped with piezoresistive pressure sensors arranged in a pentagonal structure to uniformly capture the contact area. A well-calibrated force platform integrated into a realistic target can provide reliable and comparable measurements of technical performance in combat sports.

Other authors who also used piezoelectric sensors include Ng and Jumadi (2022), who developed an IoT-based system to assess reaction time, kick impact force, and a flexibility index in Silat athletes. Their prototype consisted of an impact platform equipped with a piezoelectric force sensor connected to a NodeMCU microcontroller. The data were displayed in real-time on a mobile application with impact force recorded at the moment the subject executed a front kick on the device. Thibordee and Prasartwuth (2014) employed a uniaxial force transducer mounted on a fixed impact target to record the force of roundhouse kicks performed by Taekwondo athletes. The system included a foam structure covered with PVC, mounted to a wall and connected to the transducer, which was calibrated using standard weights. Aguiar de Souza and Mattos (2017) built a Wheatstone bridge using four strain gauges integrated into a Makiwara, a vertical striking board made from jatobá wood for karate, with a rice straw pad as the cushioning surface.

While strain gauges presents high long-term reliability, it should be implemented in a rigid structure that allows for correct deformation of the sensor. It also requires an energy-dissipating surface such as foam, which makes the entire system more bulky and less practical for integration into wearable designs. In contrast, piezoresistive sensors, being flexible, thin, and structurally small, allow for easier integration, such as in dummies with irregular or non-flat surfaces. However, the disadvantage of this technology lies in its long-term instability, requiring frequent recalibration to maintain data reliability.

Among accelerometers, Sant'Ana et al. (2017), positioned on the athlete's ankle to record leg acceleration during a roundhouse kick. Based on these data, and assuming the mass of the segment, the magnitude of the force was estimated, in this case represented as gravitational acceleration. This approach demonstrated sensitivity to fatigue conditions, though its precision depends on the biomechanical model employed. Liu et al. (2024), use a single accelerometer sensor on the waist for taekwondo kick recognition and Jang et al. (2022) analyzes Taekwondo kicks using inertial and impulse data.

Despite technological advances in sports performance analysis—such as the use of force platforms, high-speed cameras, force sensor systems, electromyography (EMG), and video-based visual stimuli—these solutions are often expensive, non-portable, and restricted to laboratory environments. This limitation hinders the ability to evaluate athletes under real training or combat conditions.

This study presents the design and preliminary validation of a wearable prototype integrated into a Taekwondo chest protector. The system combines piezoresistive force sensors encapsulated in Room Temperature Vulcanizing (RTV) silicone rubber and visual stimuli via LED strips, enabling real-time measurement of both response time and impact force during the execution of the Bandal Chagui (roundhouse kick) technique.

Unlike previous studies that performed these measurements using static equipment, such as fixed rectangular targets (Thibordee and Prasartwuth, 2014; Ng and Jumadi, 2022), or in laboratory environments that restricted mobility due to the use of EMG systems (Sant'Ana et al., 2017; Ervilha et al., 2020), this work proposes a portable, low-cost solution integrated into a piece of equipment commonly used in both training and competition in Taekwondo, allowing for more contextualized assessment.

The main objective of this work is to develop and evaluate a low-cost, portable system capable of reliably measuring these performance parameters in realistic training environments.

2 METHODOLOGY

Figure 1 presents the block diagram of the developed prototype that includes a piezoresistive sensor system (PSS), a visual stimulus module, a signal conditioning and acquisition system, and a user interface (UI)

2.1 Piezoresistive Sensor System (PSS)

The primary objective of the PSS is to measure the impact force generated during the execution of the Bandal Chagui technique. To achieve this, a set of piezoresistive sensors (PS) was integrated into the lateral sections of a commercially available Taekwondo chest protector, size 3. The physical space available in this area limited the design of the module to a total volume of 220 × 220 × 12 mm.

Piezoresistive sensors (C40 Model, MoreSunsDIY) with a 150 kg capacity were symmetrically distributed within the defined area. These were fully encapsulated in RTV silicone rubber to protect their structure and ensure stable contact during impact. The structure of the PSS was specifically designed to channel and transfer the majority of the impact force directly to the sensors while ensuring proper integration inside the protector.

2.2 Visual Stimulus

To emit the visual stimulus, two LED strips were integrated onto each shoulder of the chest protector, with the purpose of indicating to the athlete which side the kick should be executed from. The activation of a specific LED strip serves as a start signal, prompting the athlete to perform the Bandal Chagui kick on the same side as the illuminated stimulus.

2.3 Electronics Implementation

The piezoresistive sensors are connected to an analog signal conditioning circuit specifically designed for this sensor array. This circuit includes individual voltage dividers for each sensor and a non-inverting summing amplifier for each PSS, with an output voltage ranging from 0 to 3.3 V, compatible with the input range of the acquisition system.

The processed signal is read by the 12-bit analog-to-digital converter (ADC) of the ESP32 microcontroller, which digitizes and transmits the data wirelessly to the user interface via Bluetooth communication.

2.4 User Interface (UI)

The user interface allows wireless communication with the chest protector and enables configuration of the number of kick repetitions and the operating mode of the training protocol. Two operational modes are available:

- Sequential mode: the system alternates between left and right kicks in a fixed order.
- Random mode: the side for the visual stimulus is selected randomly.

Additionally, the UI provides real-time graphical visualization of the collected data, including impact force and response time for each kick performed, clearly indicating the corresponding laterality.

2.5 Calibration Procedure

For the calibration of the piezoresistive sensors, ten weights of 45 lb ($\approx$ 20.41 kg each) were used. The sensor response was initially recorded with a single weight, and the remaining weights were progressively added, stacking one over another at 5-second intervals.

The systematic recording of the data allowed for the construction of a characteristic curve that describes the relationship between the applied force on the sensors and their electrical response (output voltage). This curve was essential for evaluating the linearity of the sensor, i.e., how proportional the output is with respect to the increasing applied force.

A linear regression model without an intercept of the form $y = mx$ was selected to ensure a direct proportionality between the output voltage and the applied force. Including an intercept in the model $y = mx + b$ led to estimation inconsistencies, where identical sensors produced disproportionate force values under the same impact conditions. Moreover, the presence of a constant term could result in negative force values when the measured voltage fell below the calibration threshold, which is physically incorrect. It was also observed that, for low-intensity impacts, small voltage variations caused significant errors in the estimated force, an effect that was minimized using the model without an intercept.

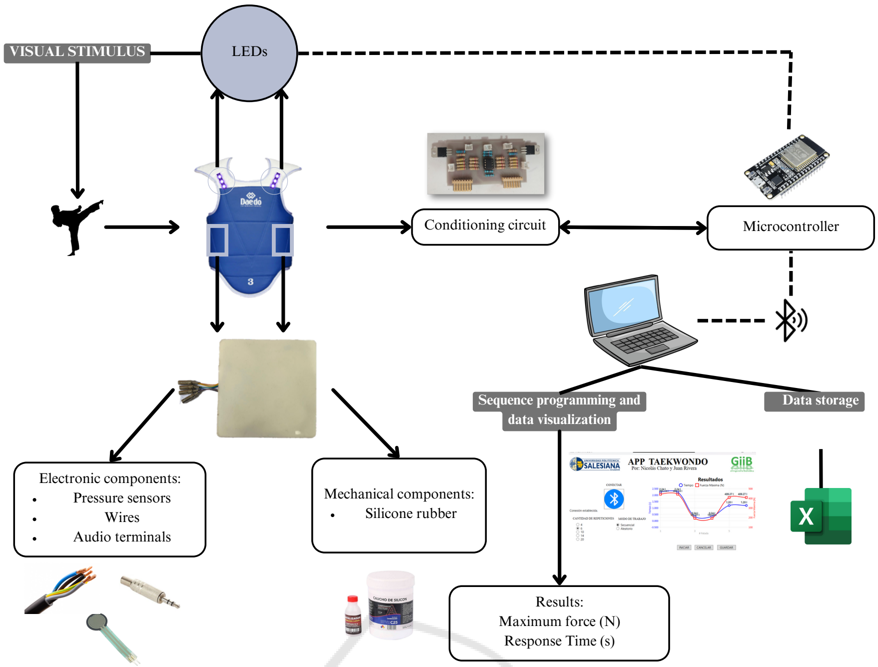

Figure 1: Block diagram of the complete measurement prototype, including sensing, data processing, visual stimulus, and user interface.

Based on this analysis, a transfer function was established (Figure 2) to interpret the sensor's output values in terms of actual physical force. Table 1 presents the calibration curve parameters for each of the sensor systems.

Finally, from the tests conducted, it was determined that the sensors exhibit drift in their behavior over time; therefore, it is recommended to perform a weekly recalibration process to maintain the reliability of the collected data.

Table 1: Calibration curve characteristics for each sensor system.

Characteristics	PSS-L	PSS-R
Accuracy	77.79%	67.05%
Linearity error	± 11.43 (% FS)	± 20.31 (% FS)
Hysteresis error	± 11.36 (% FS)	± 12.95 (% FS)
Total error	± 16.12 (% FS)	± 24.09 (% FS)

2.6 Evaluation

To evaluate the effectiveness of the prototype in a real-world setting, an experimental protocol was designed. All selected individuals had prior experience in the sport and were in adequate physical condition to perform the required tasks.

The protocol was validated by a Taekwondo coach.

Participants. The study included six active Taekwondo athletes, selected by the coach. Participants ranged in age from 20 to 43 years old. All had a minimum of three years of experience and trained at least three times per week. Among them, one athlete was 43 years old and had 27 years of experience. No beginners or individuals with recent injuries were admitted to the study. A demographic and athletic profile was collected from each participant at the beginning of the session, including leg dominance, which was self-reported through a short form completed by the athletes. All participants signed an informed consent form and attended the session wearing comfortable sportswear.

Experimental Setup. The tests were conducted using the instrumented chest protector, which includes a system of piezoresistive sensors and visual stimuli delivered via lateral LED strips (see Figure 3). To ensure a standardized distance between the participants and the impact target (the chest protector), the distance from the iliac crest to the ankle malleolus of each athlete was measured. A reference line was then marked on the floor at 15 cm less than this distance, indicating the position from which the kick should be executed.

Furthermore, the height of the impact target was adjusted individually for each participant, set to the height of the iliac crest plus 15 cm. This configuration

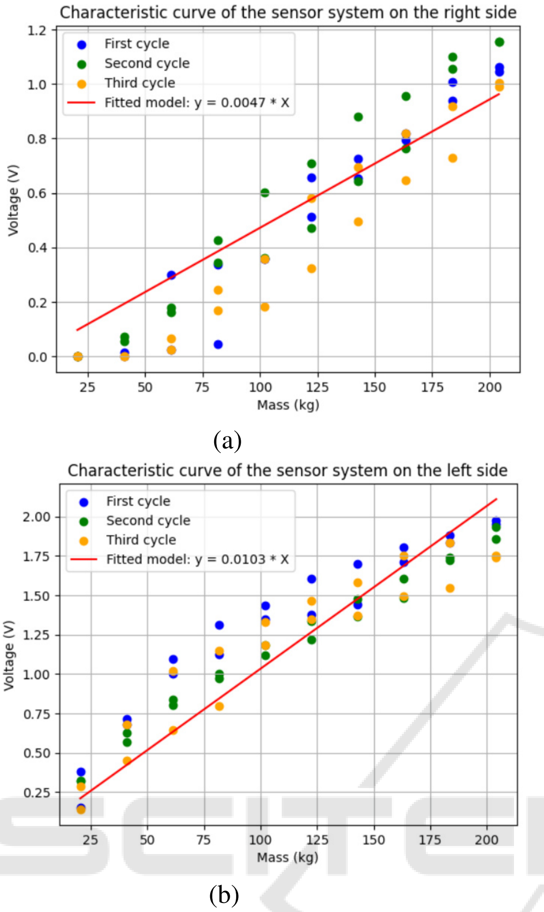

Figure 2: Characteristic curves of the sensor system: (a) right side, (b) left side.

allowed for a standardized and body-proportionate reference for all athletes (see Figure 4).

Experimental Protocol. The complete procedure lasted approximately 25 min per participant and was divided into the following stages:

Informed consent: The purpose of the test, ethical considerations, and data usage were explained to each participant. In accordance with the principles of the Declaration of Helsinki, all participants were informed about the objectives of the study, the procedures involved, the potential benefits and risks, and the voluntary nature of their participation. They were also notified about the confidentiality and protection of their personal data, as well as their right to withdraw from the study at any time without consequences.

Preparation: Personal data such as full name, age, height, weight, years of Taekwondo practice, and weekly training frequency were recorded. Then, participants performed a warm-up exercise consisting of three sets of 15 squats at 90 degrees, at a pace of one squat per second, with 30 s of rest between sets. While the warm-up was performed, the researchers configured the appropriate height and distance of the setup for each athlete (see Figure 4).

Figure 3: Location of the components on the chest protector. Red circles indicate the position of the piezoresistive sensors, while black circles indicate the placement of the LED strips for visual stimulation.

Procedure: Each participant performed the Bandal Chagui technique under two visual stimulus conditions: A. Sequential mode: Six repetitions were performed in response to alternating LED signals indicating left and right sides. After a 30-s rest, the cycle was repeated twice, for a total of 2 cycles. B. Random Mode: LED indicators were triggered in a random order, and the participant had to respond by kicking on the corresponding side. Again, 6 repetitions per cycle were performed, with 30 seconds of rest between cycles, for a total of 2 cycles.

During the experimental session, subjects were video recorded from the sagittal plane, starting from the warm-up phase through the completion of the tests. This footage was used solely for documentation purposes. Faces were blurred in all recorded material to ensure the privacy and anonymity of the participants. At the end of the session, participants completed a brief user feedback and recommendation survey, accessible via a QR code. This survey collected qualitative data on the perceived usefulness, usability, and suggestions for improvement of the prototype.

Table 2: Average values of impact force and response time (RT) during the Bandal Chagui technique for each participant. R = Right leg; L = Left leg.

Subject	Weight (kg)	Dominant Leg	Force Seq (N)	Force Rand (N)	RT Seq (s)	RT Rand (s)
1	59	Right	705 (R) 565 (L)	535 (R) 529 (L)	0.628 (R) 0.589 (L)	0.700 (R) 0.670 (L)
2	50	Right	501 (R) 201 (L)	288 (R) 114 (L)	0.878 (R) 0.897 (L)	0.929 (R) 1.108 (L)
3	59	Right	300 (R) 246 (L)	321 (R) 173 (L)	1.314 (R) 1.047 (L)	1.479 (R) 1.327 (L)
4	60	Right	629 (R) 423 (L)	583 (R) 436 (L)	1.385 (R) 0.900 (L)	1.370 (R) 0.994 (L)
5	49	Right	565 (R) 507 (L)	536 (R) 334 (L)	0.929 (R) 0.918 (L)	1.123 (R) 1.008 (L)
6	60	Left	278 (L) 310 (R)	480 (L) 352 (R)	1.115 (L) 0.818 (R)	1.001 (L) 0.809 (R)

Figure 4: Experimental setup configuration for testing the instrumented chest protector. Red lines indicate participant-specific distance adjustments made to ensure proper alignment and comfort.

3 RESULTS AND DISCUSSION

The experiment was conducted with six subjects. Impact force and response time were evaluated during the execution of the Bandal Chagui technique under two conditions: sequential (alternating visual stimulation) and random (unpredictable visual stimulation). The results are summarized in Table 2.

An average decrease of 8.16 % in impact force was observed during the random condition compared to the sequential condition. Response time increased by an average of 10.78% under the random condition.

In most cases, the dominant leg produced a higher impact force than the non-dominant one. However, during the random trials, this difference tended to decrease, likely due to the additional cognitive demand associated with rapid decision-making. Only one participant (with left-leg dominance) showed a significant increase in force from the non-dominant leg under the random condition.

All participants showed an increase in response time during the random condition and a decrease in impact force, except for one case (Participant 6), who improved in both force and response time.

This suggests that the unpredictability of the visual stimulus negatively affects technical performance, likely due to increased demands in cognitive processing and motor planning.

The developed prototype demonstrated the ability to estimate both impact force and response time in out-of-laboratory conditions with Taekwondo athletes. This allowed for testing in a more contextualized environment for measuring these parameters (Paul et al., 2016), which showed differences when sequential and random visual stimulation modes were applied. The increase in response time observed under the random mode suggests a higher cognitive load associated with the unpredictability of the visual stimulus (Mickevičienė et al., 2018; Mudric et al., 2015). Some authors, such as Shen and Franz (2005), suggest that this increase is more closely related to movement execution speed rather than cognitive processing or motor preparation. However, other studies, such as Mickevičienė et al. (2018), indicate that task complexity affects both reaction time and movement speed, supporting Hick's Law (Proctor and Schneider, 2018). Therefore, cognitive processing and decision-making may have influenced the athletes' response times.

Both perspectives—the one proposing that reaction time remains constant and only execution time is affected (Shen and Franz, 2005), and the one suggesting that both reaction time and movement speed are influenced by task complexity (Mickevičienė et al., 2018)—converge on the same outcome: a decrease in execution speed. This reduction in speed may be one of the factors explaining the observed decrease in impact force under more complex conditions. Generating explosive force, particularly in techniques such as the Bandal Chagui (roundhouse kick), requires producing a high amount of force within a short period of time (Corcoran et al., 2024). Moreover, during the execution of the Bandal Chagui in random mode, it was observed that some athletes reacted even when the striking leg was in a forward stance—a position that reduces the impulse needed to generate greater force, although it enables faster execution.

This prototype may be useful for coaches and athletes, as it enables performance evaluations in more realistic contexts than traditional laboratory methods. Its portability opens up possibilities for application during sparring (Kyorugui) training sessions involving human intervention. This would allow for athlete assessment under more complex and competition-like conditions. Additionally, it may support the development of training programs focused on improving both response time and impact force under conditions of uncertainty and movement. A major limitation was the instability of the sensors, which led to calibration errors that may have affected some of the recordings. Furthermore, the small sample size limits the generalizability of the results. Future studies should include a larger and more diverse sample with varying skill levels and categories. It would also be beneficial to improve the accuracy of the force measurement system to achieve results that better reflect real-world performance. Finally, incorporating an electromyography (EMG) system to record muscle activation could allow for more precise segmentation of reaction time in response to complex visual stimuli in realistic scenarios.

4 CONCLUSIONS

This work provides preliminary evidence on the feasibility of using wearable systems to assess Taekwondo performance. The results obtained in out-of-laboratory conditions showed differences between the sequential and random testing modes, suggesting that increased cognitive load negatively affects technical performance. However, certain limitations should be acknowledged, including sample size constraints (n=6) limiting statistical generalization, sensor drift requiring weekly recalibration, and evaluation restricted to Bandal Chagui technique on chest protectors. Despite these limitations, this work represents an initial step toward a tool capable of measuring key parameters such as reaction time and response time in contextualized environments—an essential aspect for evaluating the true nature of the sport. The system demonstrated consistent behavior and clear potential for further improvement. Future research could focus on increasing the number of participants and applying inferential statistics to provide evidence of differences between sequential and random modes, integrating electromyography (EMG) to measure reaction time and validating the prototype in competition sessions

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