Original Article

In-Field Recording of Six Biaxial Angles and Plantar Pressures in Weightlifting through a Wearable System

Abstract

Background: Monitoring and evaluation of the techniques used in weightlifting are based on the subjective observation of the coach, which can ignore important aspects of short duration. This study aimed to implement an embedded system to register the angular variation of the hip, knee, and ankle joints, and plantar pressure during training. **Methods:** Four professional and four amateur athletes performed five snatch lifts. To evaluate the angular measurement, the tests were simultaneously videotaped and the results were contrasted. **Results:** The angular data presented a correlation coefficient of 0.92 and a delay of 495 ± 200 ms. The characterization of the sensors was implemented in a microcontroller with a mean absolute percentage error of 18.8% in the measurements. When comparing the average results between the elite and amateur groups, the amateur group performed a delayed descent in the first three phases of the lift and an accelerated descent in the fourth phase. A not uniform plantar pressure was registered in the same group, causing a reduction in the final speed of recovery with the barbell. **Conclusions:** The proposed system has been developed for biaxial angular registration of hip, knee, ankle, and plantar pressure during weightlifting snatch. The option to contrast between signals presented by the system met the requirements requested by the coaching staff and is seen as a promising quantitative analysis tool to support the coach and the athlete.

Keywords: *Inertial sensor, plantar pressure, snatch, weightlifting*

Miguel Fernando Cárdenas-Rodríguez, Cristhian Geovanny Paute-Tigre, Freddy Leonardo Bueno-Palomeque

Applied Embedded Hardware Research Group (GIHEA), Universidad Politécnica Salesiana, Cuenca, Ecuador

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Introduction

In Ecuador, weightlifting has become one of the sports with the greatest achievements in international competitions, reaching the podium at the Tokyo 2020 Olympic Games in the women's category 76 and 87 kg. The snatch technique is the first lift with which weightlifting is competed in weightlifting; it consists of lifting a barbell above the head from the ground in a single movement. To achieve this lift, high speed and a wide arc of mobility are required and in this execution, the athlete's posture plays a fundamental role.[1,2] The distribution area and pressure levels supported by the feet during the execution of the exercise are fundamental to improve technique and training in general.[3]

The application of electro-mechanical technological devices in the process of monitoring and evaluation of the technique performed is an important factor in the training of elite athletes. On the other hand, the application of technological equipment in the training process in amateur athletes is limited; however, its application could reduce the risk in its execution and timely feedback on the performance of athletes.[4] In this aspect, the application of small and low-cost wearable devices is breaking the barrier of technological access among elite and amateur athletes and its application has been increasing exponentially in recent years.[5,6] One of the challenges facing research in this area is the transition of the application of sensors from the laboratory to the field of application, both for energy independence, environmental parameters of work, and the impact of its use in the development of the sporting activity.

Inertial sensor technology has been proposed in different human locomotion activities and has demonstrated its potential in different sports areas.[5,7,8] The proposal by Flores-Morales *et al*. presents the use of MPU 6050 inertial sensors for goniometric

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Address for correspondence:
M.Sc./Eng. Freddy Leonardo Bueno-Palomeque, Grupo de Investigación en Hardware Embebido Aplicado, Universidad Politécnica Salesiana, Cuenca 010102, Ecuador.
E-mail: fbueno@ups.edu.ec

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measurement and for recording angular variation during human gait. Although the processing speed of the system did not allow for recording dynamic activities beyond gait, the proposed algorithm is applicable for faster system design by upgrading the inertial hardware.[9] The application of a 3-axis accelerometer (PS-2136A) on the barbells analyzed the vertical plane in the execution of the first thrust, transition, and second thrust in the power start. A high correlation was found here when comparing the recording with the 3D video in the Z axis, but not so in the X and Y axes.[10]

Complementing the acquisition of data through a network of sensors enhances the immersion of technologies in the area of sport, and provides the training team with information at different levels and for different parameters. The use of pressure sensors, for example, has played an important role in the recording of postural pressures, where sensors are designed and implemented to monitor areas of body contact where an excess of pressure for long periods can cause the appearance of pressure ulcers.[11] Another alternative, where wearable flexible pressure sensors are used to monitor the forces in three dimensions generated on the knee to provide supportive feedback in training or rehabilitation processes.[12]

This preliminary study describes the development and testing process of an embedded system for biaxial recordings of six postural angles (hip, knee, and ankle, in both limbs, in the frontal and sagittal plane) and plantar pressures (hallux, the first and fifth metatarsal head, and heel) during weightlifting snatches. The system consists of two instrumented insoles and an electronic system for biaxial angular measurement of the lower extremity joints. The recorded data were sent wirelessly to the computer to be stored and processed together with the athlete's data in a database. The user interface was designed under the guidelines of the trainees, focusing on the comparison of the pressure and angular variation curves between the performance developed by an elite athlete and an amateur athlete, to provide feedback on the training process.

Methods

The development of the system was organized into four blocks:

- The first block consisted of instrumented insoles to quantify force levels at four points on each foot
- The second block consisted of a wearable system for biaxial angular measurement (frontal plane and sagittal plane) in the hip, knee, and ankle joints
- The third block consisted of an electronic system to receive, process, and wirelessly send the collected data
- The fourth block was a user interface for data recording and processing.

The first sensor block consisted of two instrumented insoles that recorded plantar pressures at four points on the sole of each foot through four Flexiforce Standard Model A201 sensors. The sensors recorded forces in a range from 100 to 1000 lb. The weight of each insole was 250 g with a thickness of 2.8 mm. The sensors were located in the posterior foot area (hereafter identified as (PTI) pressure on left heel, (PTD) pressure on right heel, for the left and right foot, based on his name in Spanish), over the hallux ((PDI) pressure on left hallux, (PDD) pressure on right hallux), over the first (Pressure on first left metatarsal (PPI), pressure on first right metatarsal (PPD)) and fifth metatarsal head (Pressure on fifth left metatarsal (PQI), Pressure on fifth right metatarsal (PQD)). The insoles were covered with elastic fabric to adapt to a range of sizes from 25 cm to 27 cm [Figure 1a]. The sensor locations in the insoles were defined in base on the regions of peak pressure data reported.[13]

For the biaxial angular measurement system, six ADXL335 accelerometers were used, connected to an electronic data-receiving card, located in the back of the user's belt [Figure 1b data management unit]. Sensors were placed on the abdomen, as shown in Figure 1b, to record hip tilt, on the rectus femoris muscle to determine knee angle, and on the tibialis anterior to determine the angle of the ankle. The recorded angle was coded by three letters. The first letter (F, S) corresponded to the frontal or sagittal body plane of registration (based on his name in Spanish). The second letter (C, R, and T) is to the hip, knee, or ankle joint and the third letter (I, D) corresponded to the left or right extremity. The location of the six sensors is shown in Figure 1b. A Teensy 3.2 development board was used to receive the data from the insoles and the angular sensors, process it and send it through Bluetooth HC-05 to a receiving computer, and through an interface created in MATLAB, the data analysis and registration were performed. Angles and its coding are shown in Figure 2.

The electronic system that makes up the third block of the system is schematized in Figure 3, where it is observed four main sections.

- Section 1: Was made up of a push button on the athlete's belt, which was responsible for manually initializing the data acquisition, this button must be push on by the athlete. The wearable system turns on and remains 5 s in the initialization stage. Through a sound signal, the athlete is warned of the start and end of the data recording. During the tests, the system was set up with a recording time of 15 s. A different sound signal was used to indicate the start and end of data transmission to the computer
- Section 2: The data from the two instrumented insoles were multiplexed. The high-speed analog switching encoder-multiplexer, CD4051BE was used. This multiplexer collected the analog signals delivered by the eight force sensors located on the insoles and sent them to the analog port of a Teensy 3.2 board, based on an ARM Cortex-M4 processor

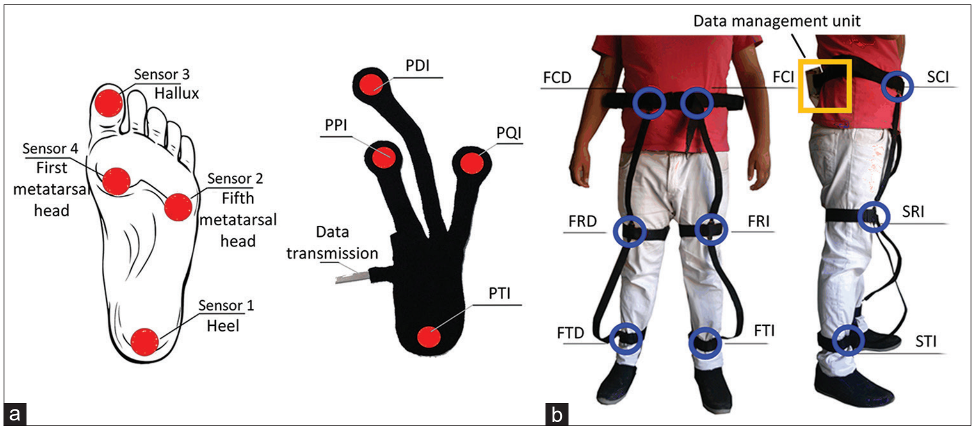

Figure 1: (a) Distribution of sensors in the instrumented left foot template on the hallux (PDD, PDI), on the first metatarsal head (PPD, PDI), on the fifth metatarsal head (PQD, PQI), and on the heel (PTD, PTI). (b) Distribution of accelerometers and their coding in the frontal plane for hip joint angle measurement (FCD, FCI), for knee (FRD, FRI), and for ankle (FTD, FTI). In the right sagittal plane, for hip joint angle (SCD, SCI), for knee (SRD, SRI), and for ankle (STD, STI). PDD – pressure on right hallux; PDI – pressure on left hallux; PPD – pressure on first right metatarsal; PDI – pressure on left hallux; PQD – pressure on fifth right metatarsal; PQI – pressure on fifth left metatarsal; PTD – pressure on right heel; PTI – pressure on left heel; FCD – frontal plane, right hip; FCI – frontal plane, left hip; FRD – frontal plane, right knee; FRI – frontal plane, left knee; FTD – frontal plane right ankle; FTI – frontal plane left ankle; PPI – pressure on first left metatarsal; SCD – sagittal plane, right hip; SCI – sagittal plane, left hip; SRD – sagittal plane, right knee; SRI – sagittal plane, left knee; STD – sagittal plane, right ankle; STI – sagittal plane, left ankle

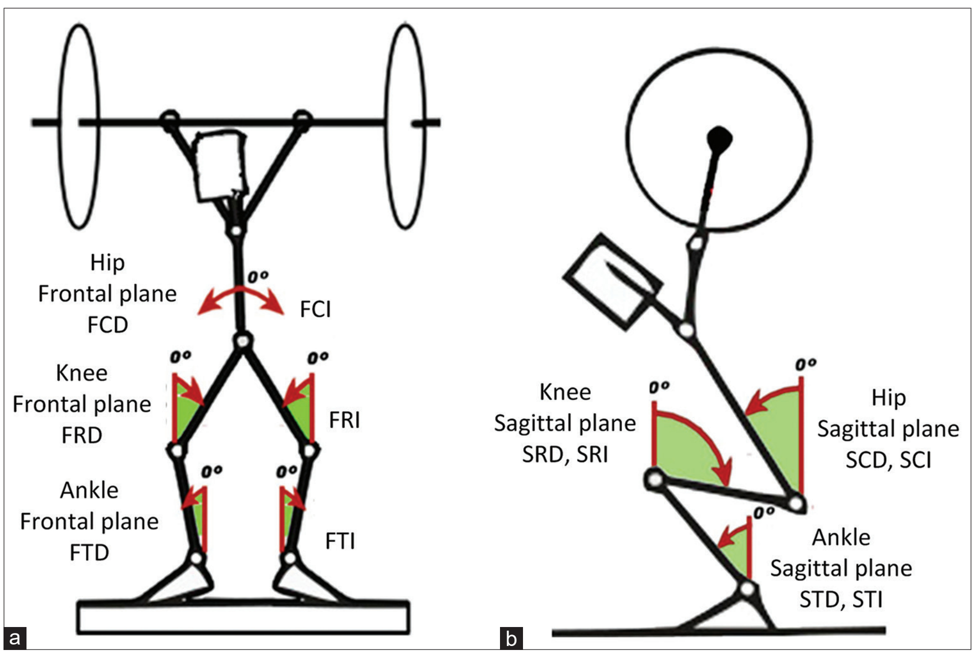

Figure 2: Angles measured by the wearable system, its coding, and direction: (a) in the frontal plane, and (b) in the sagittal plane. Red arrows indicate the angular direction that was considered positive. FCD – frontal plane, right hip; FCI – frontal plane, left hip; FRD – frontal plane, right knee; FRI – frontal plane, left knee; FTD – frontal plane right ankle; FTI – frontal plane left ankle; SCD – sagittal plane, right hip; SCI – sagittal plane, left hip; SRD – sagittal plane, right knee; SRI – sagittal plane, left knee; STD – sagittal plane, right ankle; STI – sagittal plane, left ankle

- Section 3: Covered angular data multiplexing. The two eleven-pin connectors on the right of the figure are used for power supply and received the analog data from the accelerometers and sent them to the analog ports of the Teensy 3.2
- Section 4: Include the organization and data transmission to a computer. The microcontroller uses a ten-bit analog-to-digital converter (ADC) port to digitize the angular and pressure data. The microcontroller transformed the accelerometers readings into degrees of inclination based on the algorithms presented in literature.[9] The calculated values and the reading of the insoles were arranged in a matrix of twenty columns to finally be sent wirelessly to a computer, using Bluetooth communication at a speed of 9600 baud. A matrix composed of 12 angular data and eight pressure data were recorded in the computer every 100 ms.

In block 4, a user interface was developed in MATLAB for data analysis and interpretation, all the interface buttons, tools, and information are in Spanish. The

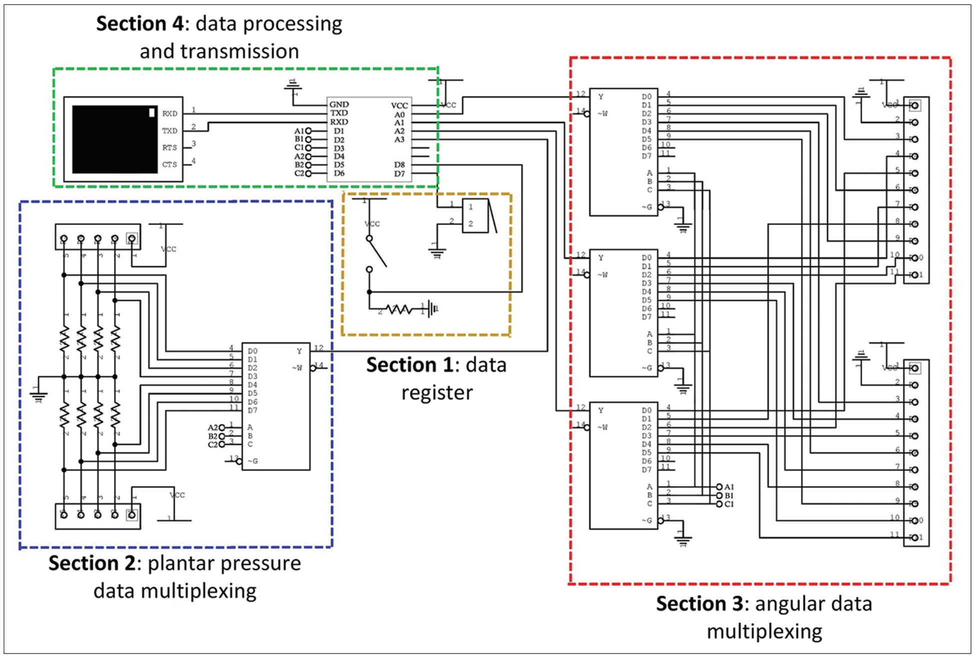

Figure 3: Schematic of the electronic circuit for organizing and sending data to the computer. Section 1 includes the process to start data acquisition, Section 2 the organization and multiplexing of analog plantar pressure data, Section 3 organizes and multiplexes the angular variation data, and section 4 the data transmission to the computer

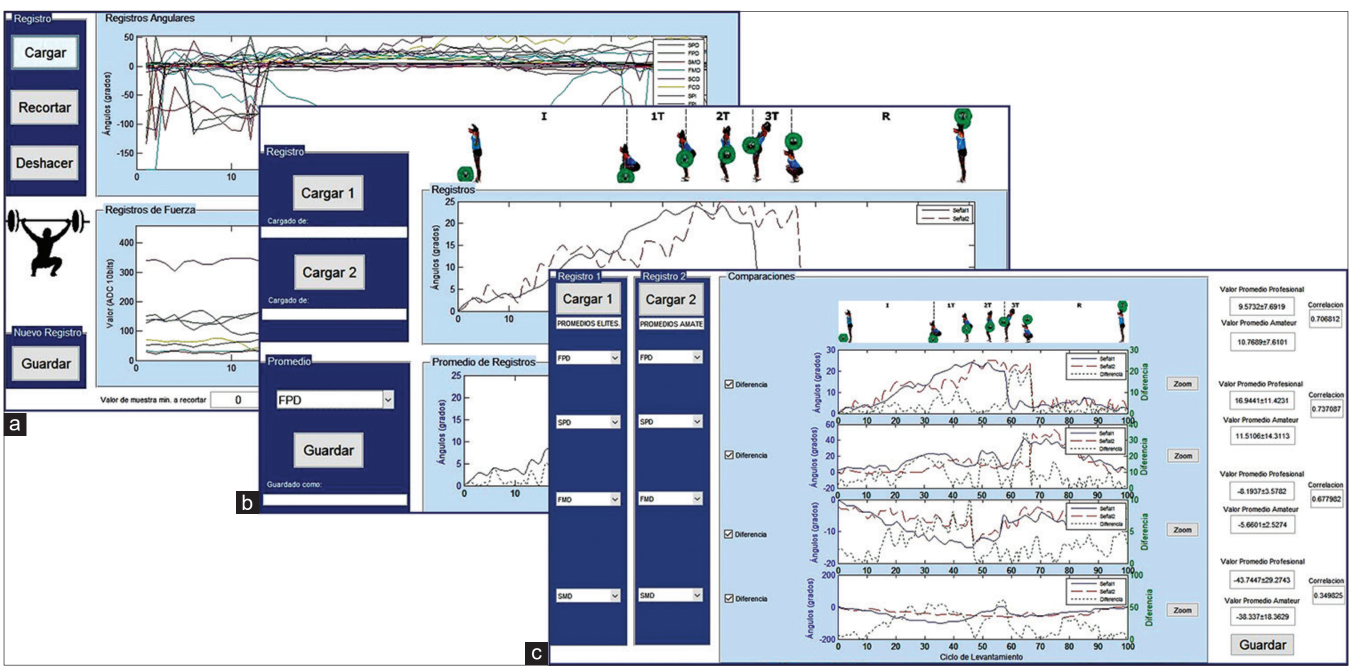

Figure 4: General view of the application sub-windows generated in the user interface developed in MATLAB. User interface: (a) first function to select and cut the range of interest data, (b) second to average data if necessary, and (c) third, to compare data

interface had three functions: Trimming, averaging, and comparing data [Figure 4]. In the first function "Trim data," it had a first button called "Load" to import a file with the data recorded by the wearable system and the instrumented insoles (data.xlsx). The data are plotted in two parts.

The upper graph shows the twelve angular records (hip, knee, and ankle, in both limbs, in the frontal and sagittal plane), and the lower graph shows the eight plantar force records (hallux, the first and fifth metatarsal head, and heel in both limbs). At this stage of the processing, the region of the samples to be used in the subsequent analysis is selected, entering in the lower margin, the min and max value of the samples. The "Undo" button recovered the original data and the "Save" button saved the trimmed data of the 20 sensors in a new file: New_data_1.xlsx [Figure 4a].

In the second function, “Average data” [Figure 4b], the “Load” button allowed the import of the data from the new_data_1.xlsx file. It made possible the import of two groups of data to average them if necessary. In the upper part of the graph, the curves of any of the twenty sensors were selected and displayed, and in the lower graph, the average signal of the two imported signals was plotted; as well as the difference between them. The “Save” button save the averaged data of the twenty sensors in a new File: New_data_2.xlsx.

In the third function, “Compare data” we had two buttons, “Load 1” and “Load 2,” which imported the data from the new_data_2.xlsx files after having gone through the trimming and/or averaging processes. In the drop-down menu of each column, it was possible to choose among the twenty sensors to display them on the right side of the application [Figure 4c]. By clicking on the “Difference” button, the difference between the two imported signals was added to the graph. Finally, the mean values, the standard deviation of each signal, and the correlation between the two signals were displayed on the right side of the screen. The “Save” button saved the difference of the signals between the two loaded files in a new file: Final_data. xlsx.

The force and inertial sensor block were tested to characterize its behavior and evaluate its performance. Repetitive tests were performed on the instrumented insoles with a force bench and a load cell. On the other hand, the validation of the measurements of the inertial sensors was performed through the contrast between the results of the proposed system and the results of the video analysis with the Kinovea software. Once the system was validated, tests were carried out with athletes to evaluate the use of the complete system. These tests were carried out in the Federación Deportiva del Azuay with four elite athletes and four amateur athletes in the snatch lift, whose age and weight information are shown in Table 1 Each athlete was evaluated with five repetitions with a lifting weight of approximately 75% of their body weight. To analyze the results, the curves were divided into five stages: In the initial phase (I), the athlete leans to reach the barbell, the first pull phase (1T) includes taking off the barbell from the floor, in the second pull phase (2T), the barbell rises to the height of the hips, in the third pull phase (3T) the athlete moves the body until it is located below the barbell, and finally, the recovery stage (R), where the bar is raised to its maximum height.

Table 1: Characteristics of the study population and weight lifted

Athletes	Age (years)	Body weight (kg)	Categories (kg)	Weight lifted (kg)
Elite 1	21	73	Senior 77	60
Elite 2	25	80	Senior 85	70
Elite 3	28	83	Senior 85	70
Elite 4	26	76	Senior 77	60
Amateur 1	15	64	Youth 69	55
Amateur 2	18	68	Junior 69	55
Amateur 3	20	72	Senior 77	60
Amateur 4	17	65	Youth 69	55

Results

To characterize the behavior of the force sensors of the instrumented insoles, tests were performed on a force bench. Seven different forces were applied to each of the sensors in a range between 0 and 535N. Figure 5 plots the data recorded in the tests performed on the eight sensors and the average curve. From this, Eq. 1 was determined using a third-order polynomial regression. The degree of the polynomial was determined based on the measurements made on the force sensors [Figure 5a] and the method of least squares analysis was used to determine the coefficients. The correlation coefficient between the average curve and (1) is $r = 0.9984$.

$$y = (1.6 \times 10^{-6})\, x^3 - 0.0014x^2 + 0.45x - 14 \qquad \text{Eq. 1}$$

Where x represent the digital value from the ADC and y is the force value in Newtons.

When comparing Eq. 1 with the vector of average forces of the sensors, a mean absolute percentage error of 18.8% was obtained, which indicates a good approximation of the polynomial [Figure 5b].

For the validation of the data recorded by the inertial sensors, the lifting tests were recorded simultaneously with the proposed system and with a Canon SX50 h camera. Five repetitions of flexion of the hip, knee, and ankle joints were recorded and the average between them was compared with the video recording. When plotting the average curve

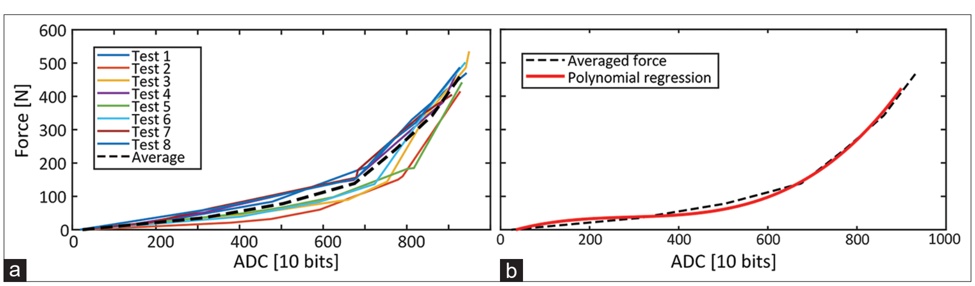

Figure 5: (a) Digital voltage registered during the eight mechanical tests on the eight force sensors (colored lines) and the average value (dotted black line). (b) Average force curve and polynomial regression implemented in microcontroller

and the curve generated in the video analysis, a mean delay of 495 ± 200 ms and an amplitude difference of ± 2°, was observed, as the difference between the blue and red curves as shown in Figure 6. Data were processed and saved in the RAM memory of the microprocessor for subsequent sending to the computer. The mean correlation coefficient calculated between the angular measurement system and the angles analyzed by Kinovea is $r = 0.92$.

For each athlete a database was generated for each of the tests performed, then, through the interface, all the acquired data was analyzed. The data recorded from the four elite athletes was trimmed and averaged to obtain pattern curves of the twelve inclination angles (hip, knee, and ankle, in both limbs, in the frontal and sagittal plane, Figure 7 shows the results for the right limb) and pressures at the four points of the sole of the feet during the lifting cycle (hallux, the first and fifth metatarsal head, and heel in both limbs, [Figure 8]). The pattern curves obtained from the elite athletes were compared with the curves obtained from the amateur athletes considering the five phases of the technique.

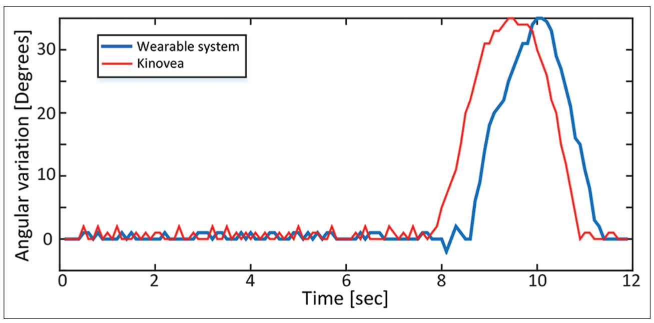

Figure 6: Angular variation curves of SCD. The average of five repetitions is plotted (blue line) and contrasted with the signal generated in Kinovea (red line). SCD – sagittal plane, right hip

The curves generated on the four elite athletes, considering the 20 sensors of the proposed system, were averaged to compare it with the amateur average; its correlation value is presented in the third column [Table 2]. In the same table, the average curves are represented with a mean value +- the standard deviation in columns two and three. The average and correlation values between elite and amateur athletes, considering the 20 sensors of the proposed system, are presented in Table 2.

Discussion

Our study aimed to develop a wearable embedded system for recording angular variation in the hip, knee, and ankle joints and to register plantar pressures at four points during the snatch technique in weightlifting. The angular and pressure results of the left and right extremities were compared, obtaining a minimum level of correlation between them of 0.95, for this reason, in the subsequent analysis; the results of one of the two extremities are considered. The results of the athletes in the elite and amateur groups are averaged to obtain a representative curve for each group. This is done because each athlete, especially in the amateur group, performed the tests with a different time duration and with particular technical characteristics corresponding at their stage in the training

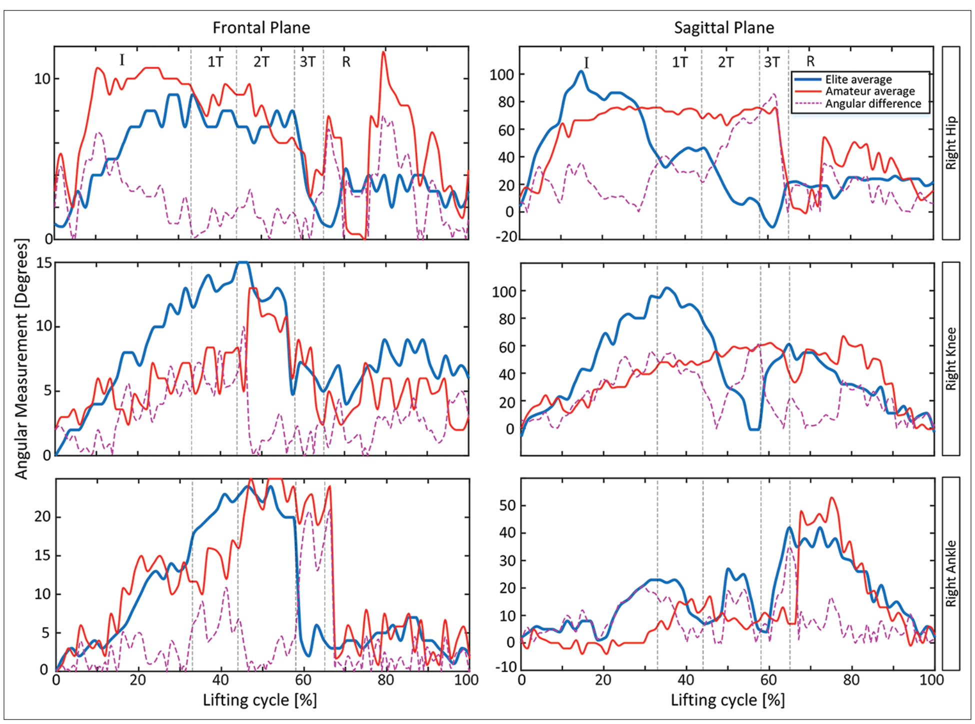

Figure 7: Variation of frontal and sagittal plane angles for the right hip, knee, and ankle. The elite and amateur groups are represented by its average (blue and red lines, respectively) and its difference is shown in pink

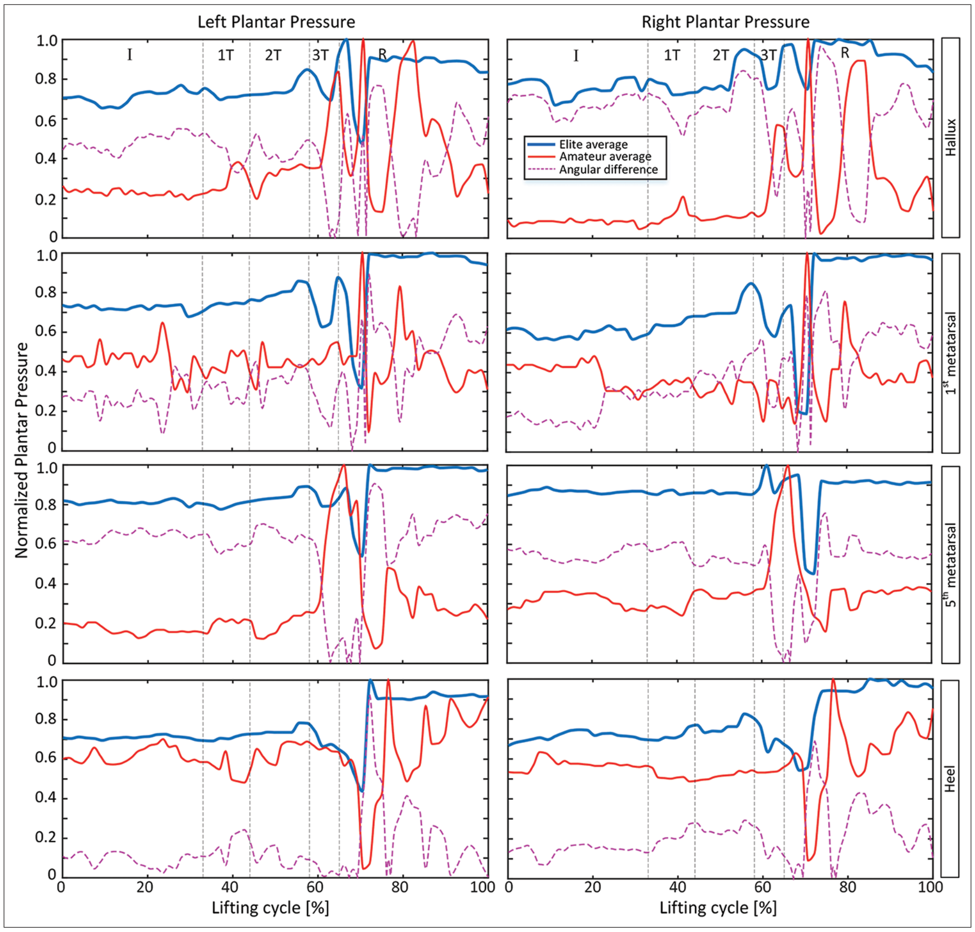

Figure 8: Variation of right and left plantar pressure for the hallux, first metatarsal, fifth metatarsal, and heel. The elite and amateur group is represented by its average (blue and red lines, respectively) and its difference is shown in pink

process. When using the application developed, the "Average data" function was incorporated, where the duration of the different tests is equalized and allows us to calculate an average signal according to requirements by the trainer.

The use of inertial sensors for the measurement of angular variation in sports applications has been probed through recording similar change patterns and slight variations in the maximum angular amplitude. In the case of Flores-Morales *et al*., using an MPU 6050 sensor, a max difference of 9.1° was observed in the knee joint data when contrasted with the video analysis.[9] In the case of the research presented by Flores *et al*., the measurements were satisfactorily validated using accelerometers in the vertical axe Z, and they suggest carefully analyzing the measurements in the X and Y axes.[10] With the use of the ADXL335 sensor, we registered a similar change pattern of angular variation with a difference in the max amplitude of ± 2° in FCI data, comparing it with the video registered. When processing the information from the six inertial sensors and contrasting it with the video record, a delay of 495 ± 200 ms was observed [Figure 6] however, this delay does not affect the visualization and interpretation of the data since the processing time, factor that causes the delay, affects the six sensors equally. In addition, when making a statistical comparison between the angular variation registered by our system and the variation.

measured through the video analysis [Figure 6 shows the plotted angles of sagittal plane, right hip(SCD)], we found a minimum correlation coefficient of $r = 0.92$, for sagittal plane, right knee (SRD), which demonstrates the system validity.

The change pattern of the angular variation curves in the first and second pulls is similar to that reported in previous studies, increasing the maximum angle at the hip, knee, and ankle reached in the second pull.[14,15] The greatest difference between these studies and our present work is evidenced in the magnitude of the maximum angles recorded in the knee joint; however, this is due to the particular posture that the athlete acquired when executing the snatch lift.

During the analysis of the curves, it was evident that elite athletes occupied approximately 33% of the lifting cycle for the start phase (I), 11% in the 1T phase, 14% in the 2T phase, 7% in the 3T phase and finally the remaining 35% in the recovery phase. On the other hand, amateur athletes invested in the initial phase (I) approximately 41% of the

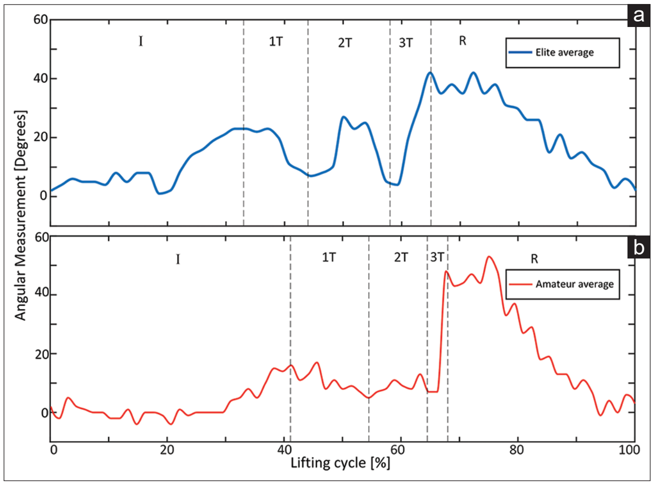

Figure 9: Comparison of the stages of the snatch lifting cycle. The threshold of the phases of the snatch cycle (I, 1T, 2T, 3T, R) was determined based on the video analysis. (a) Graph of the average of the elite group in STD (blue line). (b)Average graph for the amateur group in STD (red line). STD :sagittal plane, right ankle

routine execution time, in the 1T phase 13%, in the 2T 11%, in the 3T 3%, and finally in the recovery phase 32% as can be seen in Figure 9. The greatest difference between the lifting phases between elite and amateur athletes can be found in the 3T phase, due to the fact that amateur athletes performed the descent with the barbell in a faster way, which implies a greater angle of inclination in the lower limbs and a greater effort to complete the recovery phase. This could cause a deficiency in technique when entering the recovery phase since the athlete needs more effort for the ascent with the barbell.

The angular variation, with respect to the frontal plane [Figure 7], showed a greater correlation between the curves registered in the amateur and elite athletes, so it can be deduced that there is no greater degree of difficulty in the correct execution of the technique in this plane. Considering the angular variation with respect to the sagittal plane of the hip, Figure 7-Hip, shows that elite athletes maintained a pronounced inclination only in the initial phase, reaching a maximum inclination value of around 100°. Subsequently, angular values below 45° were reached during 2T and 3T phases to finally maintain an angle of approximately 20°. Amateur athletes, on the other hand, maintained an angle of 75° during the first four phases, and only in the recovery phase, the hip inclination dropped to approximately 40°, which may be related to an excessive load on the back to lift the barbell by amateur athletes.

With respect to the knee joint, in the elite group, the inclination with respect to the sagittal plane reached a max of 108 and 60° during 35% and 65% lifting cycles approximately. On the other hand, amateur athletes reached a max angle of 60 and 65° in 60% and 78% of the lifting cycle. This fact allowed evidence that the elite athletes use the muscular strength developed by the thighs and legs

Table 2: Mean±standard deviation of the average curves of the elite versus amateur athletes and its correlation

Sensor	Elite	Amateur	Correlation (*r*)
Frontal plane - right (degrees)			
FCD	4.9±2.4	7.0±3.0	0.59
FRD	8.2±3.6	5.7±2.5	0.67
FTD	9.6±7.7	10.8±7.6	0.70
Frontal plane - left (degrees)			
FCI	5.3±3.0	4.2±3.2	0.67
FRI	7.9±3.3	3.8±2.4	0.67
FTI	10.5±7.4	9.2±5.6	0.56
Sagittal plane - right (degrees)			
SCD	37.6±28.4	50.8±24.5	0.36
SRD	43.7±29.3	38.3±18.3	0.34
STD	16.9±11.4	11.5±14.3	0.73
Sagittal plane - left (degrees)			
SCI	37.0±31.8	53.2±29.8	0.53
SRI	44.1±27.9	32.4±19.4	0.34
STI	16.61±11.5	7.7±13.2	0.66
Plantar pressure - right (normalized)			
PDD	0.8±0.1	0.2±0.2	0.47
PPD	0.7±0.2	0.4±0.1	−0.06
PQD	0.9±0.1	0.4±0.1	0.21
PTD	0.8±0.1	0.6±0.1	0.51
Plantar pressure - left (normalized)			
PDI	0.8±0.1	0.4±0.2	0.29
PPI	0.8±0.1	0.5±0.1	−0.28
PQI	0.9±0.1	0.3±0.2	−0.05
PTI	0.8±0.2	0.6±0.1	0.34

FCD – frontal plane, right hip; FRD – frontal plane, right knee; FTD – frontal plane right ankle; FCI – frontal plane, left hip; FRI – frontal plane, left knee; FTI – frontal plane left ankle; SCD – sagittal plane, right hip; SRD – sagittal plane, right knee; STD – sagittal plane, right ankle; SCI – sagittal plane, left hip; SRI – sagittal plane, left knee; STI – sagittal plane, left ankle; PDD – pressure on right hallux; PPD – pressure on first right metatarsal; PQD – pressure on fifth right metatarsal; PTD – pressure on right heel; PDI – pressure on left hallux; PPI – pressure on first left metatarsal; PQI – pressure on fifth left metatarsal; PTI – pressure on left heel

for the thrust, which is correlated with the greater flexion angle recorded; while the amateur athletes exerted a greater effort in the legs to perform the thrust during the recovery phase, reaching their greatest angular variation at this stage [Figure 7-Knee].

When analyzing Figure 7-Ankle, it can be observed that the curve STD of the elite athletes, had three very important and pronounced angular changes during the completely lifting cycle, due to the three descents that the athletes performed with the barbell. The variations reached values close to 23°, 27°, and 42°, in 32%, 49%, and 65% of the lifting cycle, respectively. On the other hand, amateur athletes reached angles close to 18°, 12°, and 50°, in 38%, 59%, and 68%, respectively. This pattern was similarly observed in the left and right extremities.

Regarding the recording of plantar pressure in the four points of interest of the two feet [Figure 8], an electronic circuit was adapted with the voltage levels recommended in the datasheet to handle high forces. When determining Eq. 1 for the conversion of magnitudes from voltage to force, new sensors were used, taking into account that the number of tests with high loads could affect the force levels sensed.

The differences in pressure between the elite and amateur groups are visible in Figure 8 and Table 2, it can be seen that the correlation coefficient rounds 0.5 on the sensors placed on the back of the left and right foot. Although the patterns of change are similar, there is no significant level of similarity. On the other hand, it was found that there are no significant differences in the distribution of plantar pressure between a group of high-level contrasted with a group of physical education students.[3]

Figure 8 shows in the initial phase, that the elite athletes hold a uniform pressure on the four points, which means that the load was better distributed on the floor. This fact facilitated the transmission of force for the transition from 1T to 2T phases. When entering the 3T phase, an increase in the pressure on the points located on the fifth metatarsal head (PQD, PQI), first metatarsal head (PPD, PPI), and hallux (PDD, PDI) can be observed. This allows an increase in the final lifting speed of the barbell. When the athlete moved into the 3T phase, there was a complete extension of the body and a rapid take-off of the sole of the foot from the platform, leaving the athlete supported almost entirely on the hallux. Finally, when entering the recovery phase, the athlete positioned himself under the barbell, adopting a deep squat position, for which he must fully support himself on the entire plantar surface until the end of the lifting cycle. In comparison, amateur athletes used a different posture in the initial phase, and greater support could be observed on the heel (PTD, PTI), followed by the first metatarsal head (PPD, PPI). During the execution of the 1T and 2T phases, it could be observed that there was an increase in the pressure registered on the fifth metatarsal head (PQD, PQI), which could be associated with a reduction in plantar flexion that may cause a reduction in the final velocity of the barbell. In the 3T phase, no sufficient lift-off of the sole of the foot was evident, and it was observed that considerable pressure was maintained on the first metatarsal head (PPD, PPI) and on the hallux (PDD, PDI). Finally, in the recovery phase, oscillations in the level of plantar pressure were observed, which might affect the transfer of force to the barbell and cause a slow final recovery speed.

Conclusions

This article presents the design and development of a system for the biaxial angular registration of hip, knee, ankle, and plantar pressures during weightlifting snatch. With the proposed system, a comparison of the distribution of plantar pressures between four elite athletes and four amateur athletes was developed. The proposed system is a quantitative analysis tool that could contribute to the process of recording and analyzing kinematic data for the coach and the athlete, to evaluate and provide timely feedback on the evolution of the technique.

The proposed system was noninvasive to the athlete and allowed him to develop weight lifting without altering the technique. The instrumented insoles were adjustable to the size of the soles of the feet of the different athletes and were comfortable thanks to the application of ultra-thin sensors connected internally by flat copper wires. The angular measurement system was adjustable to the flexion and extension of the lower extremities. The proposed system allows contrasting the kinematics between elite and amateur groups as feedback for the training team. In the tests performed in the Federación Deportiva del Azuay, important differences were found in the angular variation, mainly in the sagittal plane. As for the plantar pressures, a lack of uniformity in the distribution of pressures during the execution of the technique was observed. In general, the design of the system allows its applicability in different sports disciplines for the recording of pressure parameters and angular variation. The future work of this project will focus on wireless communication between the inertial sensors and the development of a mobile application for more agile monitoring.

Authors' contributions

MFCR and CGPT carried out the design, literature search, data acquisition, and data analysis. FLBP carried out the concept, data analysis, statistical analysis, manuscript preparation, editing, and review. All authors have read and approved the content of the manuscript.

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Conflicts of interest

There are no conflicts of interest.

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