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Design and analysis of a new brake-by-wire system using machine learning

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ABSTRACT

One of the main aims of the recent research on brake-by-wire systems is to decrease mechanical components. In this paper, we propose replacing the brake pedal with a driving wheel that is fully covered by pressure braking batch sensors. The new mechanism for braking translates pressure exerted through the driver's hands on the driving wheel to a corresponding electrical signal. A proposed design for the pressure braking batch (PBB) is made out of a mesh of conducting threads separated by a resistive sheet. To the best of our knowledge, this idea has not been raised before in other research papers. Different people have different muscle strengths and so the problem of identifying the intention of the user when pressing the PBB is tackled. For this aim, a new dataset of its kind is created by several volunteers. From each volunteer, age, gender, body mass index (BMI), and maximum pressure exerted on the driving wheel are collected. Using Weka software, the detection accuracy is calculated for a new volunteer to know the intention of his/her pressure on PBB. Among the three algorithms tried, the regression tree gives the best results in predicting the class of the pressure exerted by the volunteers.

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1. INTRODUCTION

The control of self-driving cars is one of the widely researched areas. The systems used to do the control have been researched in many papers not only from an engineering perspective but also from the regulating rules [1], [2]. The electric power required to operate self-driving cars is supplied from batteries. Batteries have two main problems which are: recharging [3]–[7] and lifetime duration [8]–[11]. One way to provide electric vehicles with an endless power supply is by using renewable energies. Renewables have been widely researched to find the optimum power to gain from them [12], [13], the engineering methods to extract power from them [14], [15], and the regulating rules to spread their use [16], [17].

Brake by wire system is introduced to enhance the implementation of self-driving cars. The advancement achieved in applying brake by wire is meant mainly to decrease the number of components in the braking system of the car that contains mechanical parts [18], [19]. Thus, the braking system becomes more time-efficient, space efficient, and produces less sound pollution [18], [19]. Brake by wire has attracted a lot of research recently. The main focus of the research is narrowed down to three issues. The first one is the interface of the electric and hydraulic parts of anti-lock braking systems [20]. The second one is the emergency brake system and how it works, and the third one is the control of the braking systems whether antilock braking system or emergency system and how both fit together [21]. We try to brief some of the research efforts done in each one of these three issues.

The next papers illustrate the efforts done to study the connection of the electrical parts with the mechanical parts. Simonik *et al.* [20] proposed a new design for a brake-by-wire actuator that can be applied using a linear motor. Yin *et al.* [22] proposed a system to predict the pedal feel at the time of braking. The pressure changes inside the braking system lead to changes in the feeling of the braking pedal [23]. To overcome this problem, the pedal feel is studied in relation to pressure changes to stabilize those changes by applying a fully decoupled brake-by-wire system [18], [23]. Mullner *et al.* [24] suggested a Simulink model that would be used as the last verification step before applying any proposed system. The aim is to find out the logical limits for the safety and environmental impacts of any new system so that real-life trials become safer.

The next papers illustrate the efforts done to study the functioning of the emergency brake system and its enhancement. Wang *et al.* [25] proposed an emergency braking system that serves the driver when the normal braking system fails. Two aims are served namely first to help the driver apply brakes safely to stop the car, and second, the performance of the emergency brake meets the same performance level as the normal brake [26], [27]. Two strategies are proposed to apply the new emergency brake system. When tested, the first strategy does not meet the aims described while the second strategy meets them [25]. Bhalla *et al.* [28] proposed a driving system that can drive the car independently at the time of having a drunk driver. The proposed system uses deep learning techniques and applies them to video images to extract data about the road and find the best way to drive the car safely [28].

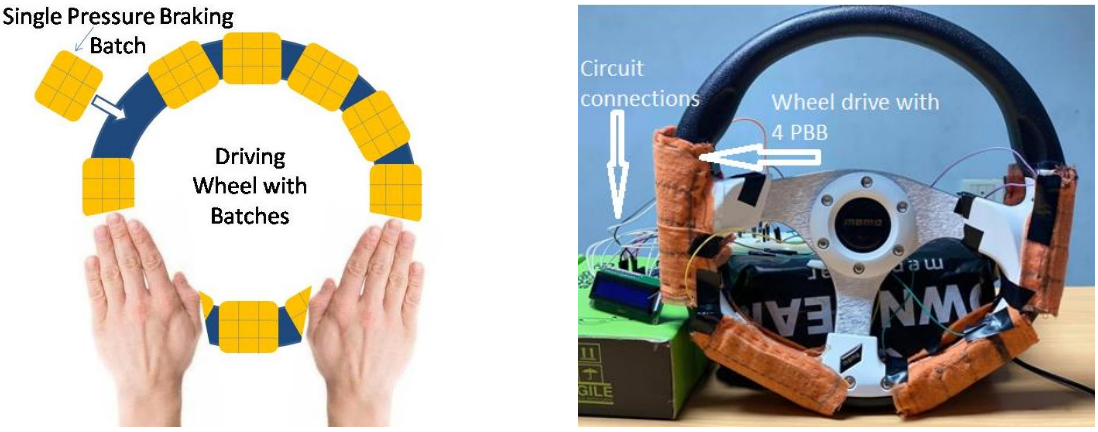
The next papers illustrate the efforts done to study the synchronization of the working of the emergency brake system and the anti-lock braking system. Montani *et al.* [29] discussed the advancement of the electronic stability system (ESC) which is responsible for the stability of the car at the time of braking before sliding happens. The proposed ESC [29] uses a linear quadratic regulator and four brake-by-wire actuators. Its main mission is to minimize the difference between the measured actual forces on the wheels and the ideal forces which should exist in a steady-state model [30]. Heydrich *et al.* [31] proposed a new system to control the movement and braking of a car to enhance safety, stability, and comfort. The system is simulated on Simulink in MATLAB to realize its effectiveness in achieving the required goals [31]. Chen *et al.* [32] proposed a new control design for the braking system of a brake-by-wire car. The new design aims at helping cars to move on unpaved roads to stabilize their braking power to have smooth running [33]. A classification method is used to measure the intention of a driver to use the brakes or not [33]. The method uses fuzzy logic to solve the classification problem [32]. The intention of divers is sensed from signals produced by human biological organs.

Biological signals are usually electric signals from the biological activity of one of the organs in the body. They are recorded using different techniques to be analyzed and find out about the characteristics of the organ [34] such as the heart. To classify these recorded signals [35], one needs to extract features from them to differentiate between the interpretation of the different signals. Preprocessing operations, such as noise removal, are usually done before feature extraction to prepare the signal. The operations are time-consuming and so avoiding them by getting the features directly from the signal [36], [37] without affecting the accuracy of classification [38]–[40] is crucial in case of emergency or when time is very important. This saves the time of the central processing unit and reduces computational time [41]. Bio-signals are usually measured in the time domain which contains a lot of data to process [42], [43]. Transforming the signal to the frequency domain has proven to be useful as it gives the user information about the spectral domain of the measured signals [44], [45]. The different transformation techniques have enabled physicians to see the measured signals from different angles of view which help in the diagnosis of a lot of diseases [46]–[48].

In this paper, we are focused on the interface between the mechanical parts namely the braking pedal and the electric wiring of the actuator. We suggest replacing the braking pedal with an electronic braking system embedded in the driving wheel which is an idea to our knowledge has not been raised before. The rest of this paper is divided as follows. Section two discusses and introduces the main idea of embedding a braking system in the driving wheel. The type and shape of the sensor embedded in the driving wheel are introduced in section three. The need for artificial intelligence and the collection of the dataset required are discussed in section four. The classification problem is illustrated and the results are shown. Finally, the conclusion and future work are drawn in section five.

2. PROPOSED PROCEDURE

The main driving force for starting the brake-by-wire concept is to decrease mechanical parts and become more time and space efficient not to mention decrease sound pollution. Along the same concept, we propose here a new method to further decrease the mechanical parts in the braking system. The new method is also a great support for disabled people who have lost control of the lower part of their body by enabling them to fully control their cars through their hands only. Throughout our daily experience with driving cars, we realized that at braking time our first reaction goes to our hands i.e., to push the driving wheel away from us as a defense mechanism accompanied by pressing the braking pedal to stop the car and avoid crashing. So here, we propose replacing the braking pedal with pressure sensors in the driving wheel. The pressure sensors are embedded all over the surface of the driving wheel as shown in Figure 1(a). A driver can simply push the driving wheel with his/her hands at the time of braking as seen in Figure 1(a). The embedded pressure sensors translate the pressure exerted on them by the driver's hands into electrical signals. The electrical signals are proportional to the amount of pressure exerted on the driving wheel. The electrical signals are then translated to an equivalent braking force to be exerted on the moving wheels of the car. To fully realize the new method, several steps have to be implemented. First, the design of appropriate pressure sensors for this application has to be thought of and realized. Second, the electronic system that is needed to collect the electric signals produced by the pressure sensors in real-time mode has to be designed in Figure 1(b). Third, the software that is needed to translate the electric signals to proportional braking power has to be programmed. When deeply thought of, we realized that there is one big problem that can severely affect the efficiency of our system. Drivers have the different muscle power to exert pressure on our embedded sensors. The proposed method has to be able to know the intention of the driver when exerting a certain pressure on the embedded sensors to be able to respond with the required amount of braking power. Artificial intelligence may be one of the solutions to this problem and so it becomes the fourth step to realize this new method. In this paper, we tackle two steps of the four mentioned above namely the first and fourth steps. The design of the pressure sensors is one issue to discuss. A simple design is taken from another application mentioned in [49] and is tailored to fit into our application. Then, the classification problem is another issue to be tackled. We need to be able to know the required amount of braking power corresponding to the different muscle forces exerted on the pressure sensors by different drivers.



(a) (b)

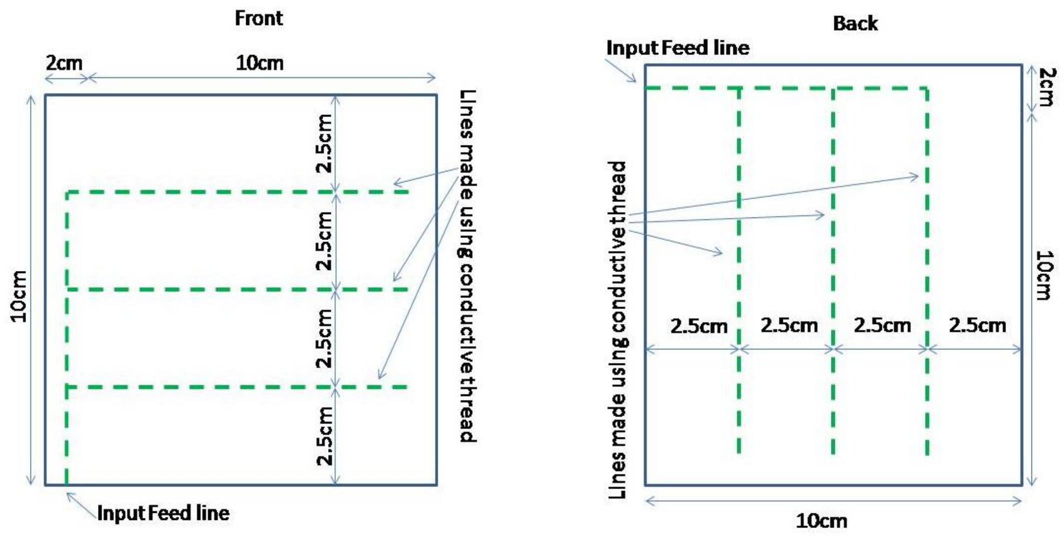
Figure 1. PBB sensor placed on the normal driving wheel: (a) 12 PBB sensors are covering the wheel, and (b) the brake pedal is replaced by a driving wheel covered by a PBB sensor

3. METHOD

Dinesh *et al*. [49] proposed a design to be used in detecting the pressure exerted on the bodies of policemen when facing violence. A similar design can be used in our proposed method to translate the pressure exerted on the driving wheel to braking power. The exact dimensions of the design were not clear, so we propose our own braking batch design. The components of the velostat sheet and conducting thread were used to realize the design. Here, we similarly use the same components.

As shown in Figure 2(a), the front (upper) side of our braking batch is composed of one vertical line which is used as a feed line. The feed line can be used to input the voltage source to the circuit of the Pressure Braking Batch. We can see another three horizontal lines. The lines are parallel to each other at a distance of 2.5 cm from each other. They can be used to form a mesh for the sensor as will be shown later. All lines are sewn by hand using conducting thread on a piece of cloth.

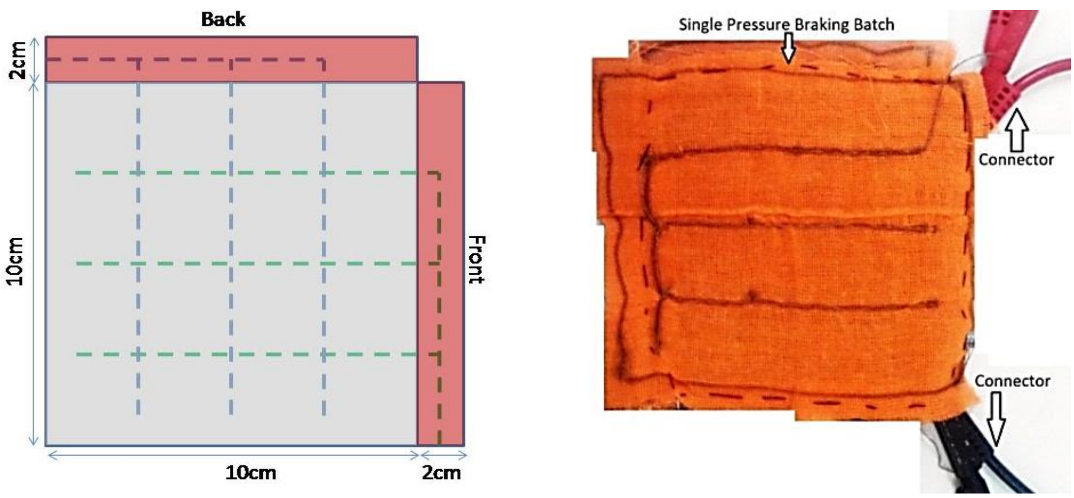
As shown in Figure 2(b), the back (lower) side is composed of one horizontal line which is used as a feed line. The feed line can be used to input the zero voltage (ground) to the circuit of the pressure braking batch (PBB). There exist three vertical lines to form a mesh as will be shown later. All lines are sewn by hand using a conductive thread on a piece of cloth made of cotton.



(a) (b)

Figure 2. The design of (a) front or upper part and (b) back or lower part of PBB sensor

The front (upper) side shown in Figure 2(a) and the back (lower) side shown in Figure 2(b) are placed on top of each other to form a mesh as shown in Figure 3(a). Nine points of contact are formed between the lines on the upper side and those on the lower side. Each feed line is placed in a way to have no corresponding point of connection or conducting line on the other side. A sheet of velostat with the size of 10 cm by 10cm is placed between the two sides to form a resistance between every two points of contact. In Figure 3(b) a realization of the design shown in Figure 3(a) is shown.



(a) (b)

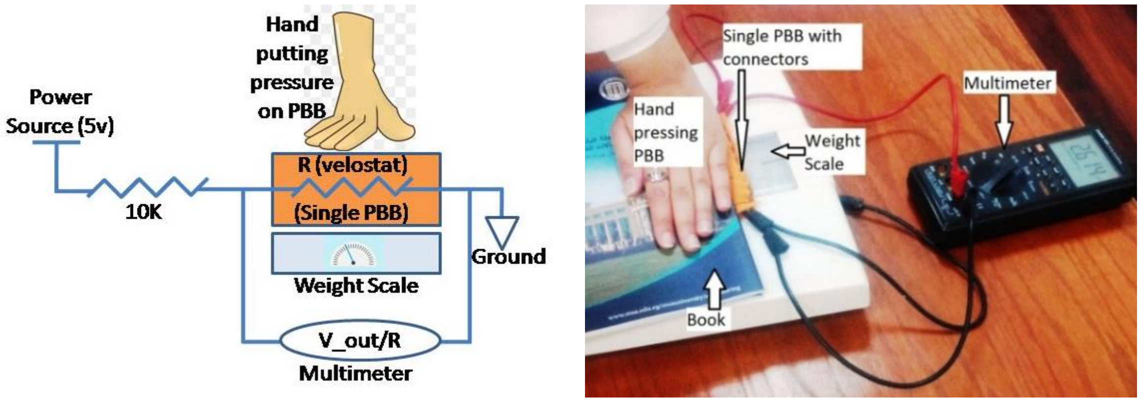
Figure 3. PBB sensor constructed and realized: (a) the front and back designs of PBB attached to form nine points of contact and (b) a handmade sensor of a single PBB implemented

In Figure 3(b), we can see the upper piece of cloth with lines drawn on it as those shown in Figures 2(a) and 2(b) using a pen. The conducting thread is sewn on the lines to form the same design as that explained before in Figures 2(a) and 2(b). The velostat sheet is not seen in Figure 3(b) as it is placed inside the batch. The lower side cloth is placed on the other side and is not seen as well. The upper side, lower side, and velostat sheet are placed parallel to each other. Next, we discuss the problem of how to translate the pressure exerted on PBB to equivalent braking power when different people with different muscle strengths use the PBB.

4. RESULTS AND DISCUSSION

We simplify and describe the classification problem as follows. Three different classes for the level of braking power are defined namely high, medium, and low braking power. A group of volunteers is asked to press the PBB to satisfy their own muscle strength in each of the three classes. For each class, a certain pressure is exerted on the PBB corresponding to this class. The exerted pressure is dependent on the muscle strength of each person. For all volunteers, a table is created that relates the measured PBB resistance to the class of the required braking power. Now for a new volunteer, the question is what the intended braking power would be for the resistance produced from pressing the PBB. This a pure classification problem for which this table/dataset has to be created. The following setup is done to create the dataset.

As shown in Figures 4(a) and 4(b), the tools used to collect our dataset are shown. A PBB is connected in parallel to a multimeter. The multimeter is used to measure the resistance of the PBB or voltage across it. The PBB is placed over a weight scale to measure the pressure exerted on the PBB in kilograms. A book is placed over the PBB to keep the layers of the PBB sensor in contact at all times. When a person put pressure on the book, the resistance of the PBB is changed. The circuit in Figure 4(a) shows the way the PBB is connected to a power supply circuit. A five-voltage power supply is connected to a constant resistance with a value of 10 kilo-ohms. The constant resistance is connected to the PBB and then to the ground. The output voltage "*Vout*" which is the output of our proposed sensor is taken at a point in between the constant resistance and the PBB.



(a) (b)

Figure 4. A multimeter, weight scale, single PBB, multimeter, and a book in (a) a sketch of the experimental setup and (b) a volunteer exerting pressure on a PBB sensor in a real setup

The circuit acts as a potential divider for which the "*Vout*" can be calculated as (1).

$$Vout = 5\ volts \times \frac{R}{10\ K\Omega + R} \quad (1)$$

where *R* is the resistance of the PBB, 10 Kilo-ohms is the constant resistance and 5 volts is the value of the power supply. The circuit is shown in Figures 4(a) and (b) is designed in such a way that it acts in a certain way at the limits. When R of the PBB is almost equal to zero (minimum) or equal to infinity (maximum), the output values of the voltage are:

If $R \approx 0$ then the output behaves as $\Rightarrow Vout \approx 0 volts$
Else If $R \approx \infty$ then the output behaves as $\Rightarrow Vout \approx 5 volts$

Three male and three female volunteers in the twenties of their ages came forward to participate voluntarily in this work. The reason for creating this dataset is explained to the volunteers and their approval is taken. For each volunteer, the following data is recorded: age, gender, body weight, and body length. Body weight and body length are used to calculate BMI which can refer to the strength of the body. Each of the six volunteers pressed with his/her dominant hand on the PBB sensor and the corresponding weight, voltage, and resistance are collected. Each volunteer is asked to press the PBB sensor with the pressure that he/she thinks satisfies the three classes: high, medium, and low. The raw data produced from one female and one male volunteer is shown in Figure 5 as an example. The female has a BMI of 18 Kg/m^2 and the male has a BMI of

33 Kg/m^2. The pressure exerted by this female participant (*F_W*) is lower than that exerted by this male one (*M_W*). One explanation for this is the difference in BMI. It is obvious that the relationship is inversely proportional between the pressure exerted on the PBB (*F_W* or *M_W*) and the corresponding resistance of the PBB sensor (*F_R* or *M_R*). However, it is equally clear that the slopes for the males and females have different rates and so the rate of decrease in the resistance produced from the velostat corresponding to exerted pressure is different for each person. The relation is also inversely proportional between the pressure exerted on the PBB (*F_W* or *M_W*) and the corresponding voltage across the PBB sensor (*F_Vout* or *M_Vout*). From these data, the classification algorithm should be able to identify, for any pressure exerted on PBB, the corresponding class of intended braking power.

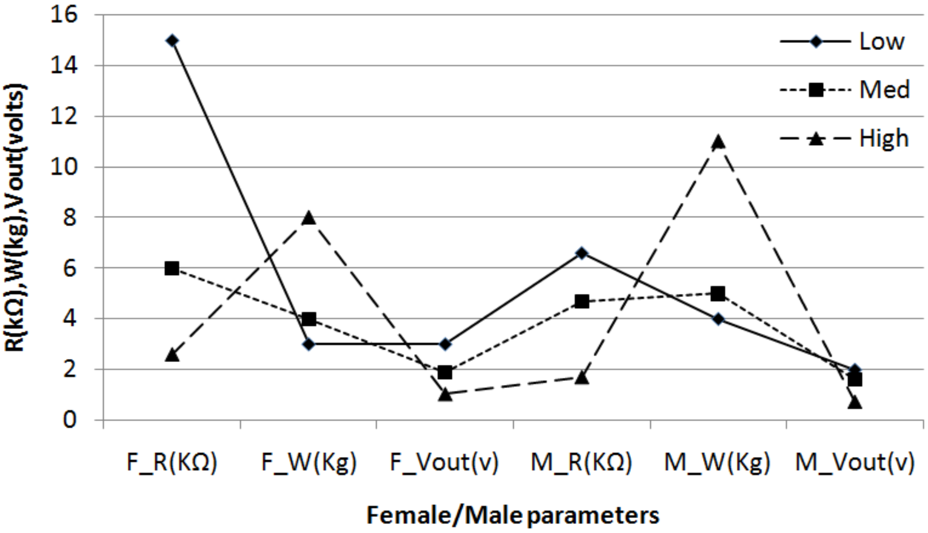


Figure 5. The raw data produced from the setup in Figure 4(b), where *F_R* is resistance in KΩ, *F_W* is pressure in Kg, *F_Vout* is output voltage in volts for a female participant, *M_R, M_W*, and *M_Vout* are for a male participant

For every person using the classification code, we use the flow of the sequence of required inputs: i) Enter age, gender, weight, and height; ii) BMI is calculated from weight and height; iii) The user is asked to exert maximum pressure on the driving wheel. Corresponding voltage is recorded; iv) The user is asked to start driving and new pressure exerted on the driving wheel is detected. Corresponding voltage is recorded; v) The voltage of maximum exerted pressure, BMI, age, and gender are used to find a class of the voltage of newly exerted pressure whether low, medium, or high; and v) The class identified in step 5 is translated into corresponding braking power.

Next, three algorithms are used to solve this classification problem. The K-nearest neighbor (KNN), naïve Bayes (NB), and regression tree (RT) algorithms are compared to find which one is the best in classifying our dataset. We describe some of the work which addresses KNN, NB, and RT. Guo [50] proposes evaluating the performance of the algorithms used in identifying the faces of people from images taken on the streets. The KNN algorithm is the selected one to be evaluated. The KNN algorithm achieves very high accuracy [51] for uncovered faces but for covered faces, the accuracy drops down below 10% [50]. Rahim *et al.* [52] used the NB algorithm to predict the errors which can happen from certain software and proposed three steps which when applied show high accuracy in detecting those errors [52]. Another paper discussed increasing the accuracy of the Naive Bayes algorithm when applied to artificial intelligence classification problems. Chen *et al.* [53] proposed using feature extraction and calibration methods to achieve improvement. Carrizosa *et al.* [54] and Aljameel *et al.* [55] studied the regression tree algorithm of classification to find out ways of increasing its accuracy. Carrizosa *et al.* [54] aimed at decreasing its time consumption and the processing power required for running it. For interested readers in the equations of the three algorithms KNN, NB and RT kindly refer to [50], [52], [54], respectively. We use the Weka software [56] to solve the classification problem. The precision percentage [56] is the criteria used to evaluate the accuracy of classification.

From Table 1, the KNN algorithm showed the worst results. The accuracy for detecting the high and medium classes is zero which makes it not suitable at all for this application. KNN is used to calculate the Euclidean distance between old data with a known class and new data with an unknown class. The least distance defines the class to which the new data belongs. As shown in Figure 5, the points which are close to each other do not belong to one certain class which makes the prediction not accurate. Some data such as gender cannot be taken into consideration inside the KNN algorithm.

The NB algorithm predicts the low class with a very high accuracy of 100%. But the detection accuracies for the high and medium classes are 60% and 57.1% respectively which is not accurate enough. The NB algorithm is based on the Bayes theorem. It is used when the class that may lead to a certain result is known. Knowing the conditional probability, we can use the reverse probability to know the class of the unknown data. As shown in Figure 5, the dataset does not follow a certain order (specifically for different genders) which makes the prediction probability of belonging to a certain class not very accurate.

For the RT, the accuracy of detection for the high and medium classes is 83.3% for both. The accuracy of detection for the Low class is 100%. The RT algorithm has proven to be the best. A regression tree is used to build a tree that connects one class to various conditions in the form of a tree. This tree can be used to find the class of an unknown condition. The dataset is based on criteria to reach a prediction of the braking power such as being male or female and also the BMI which makes the RT the most relevant to apply to this dataset.

Table 1. Accuracy of true detection for the three classes high, medium, and low

Accuracy	KNN	NB	RT	
	0.0%	60.0%	83.3%	High
	0.0%	57.1%	83.3%	Medium
	100.0%	100.0%	100.0%	Low
Avg.	33.3%	72.4%	88.9%	

5. CONCLUSION

The modern advancement in the braking system of the car dictates that mechanical parts are replaced by electrical parts. Towards this aim, we propose replacing the brake pedal with a driving wheel that is fully covered by pressure sensor batches. The new mechanism for braking is to put pressure through the driver's hands on the driving wheel which is translated to a corresponding electrical signal. This should replace the old mechanism which depends on pressing the brake pedal through the driver's legs to be translated to an electrical signal or mechanical system. A proposed design for a PBB is shown. The design is made out of a mesh of conducting threads which are separated by a resistive sheet. The pressure exerted on the sheet causes the resistance to change. Velostat sheets, conductive threads, and pieces of cotton cloth are used to realize the proposed sensor. A person pressing the PBB sensor causes a change in the resistance of the PBB. Different people have different strengths and so the problem of identifying the intention of the user when pressing the PBB is tackled next. A dataset is created with the help of several volunteers. Several data are collected from each volunteer such as age, gender, and BMI. Also, each volunteer is asked to press the PBB sensor three times to satisfy the volunteer's point of view: high, medium, and low braking power. Using Weka software, the detection accuracy is calculated for a new volunteer to know the intention of his/her pressure on PBB. The three algorithms used are KNN, NB, and RT. The RT gives the best results in predicting the class of the pressure exerted by the volunteers. In this paper, five fruitful results have been achieved. We present the design of a new brake-by-wire system, create a new dataset of its kind to implement the new braking system, find the best classification method suitable for the new dataset, design a pressure braking batch sensor, and articulate the sequence of inputs required from every new user.

Next, we compare the computational complexity of the three tried classification algorithms. The computational complexity of the KNN and NB depends on the number of features and number of incidents recorded which can be very large. However, the computational complexity of RT depends on the number of branches in the tree which is 4 in our case here which is very simple and faster. A number of shortcomings in our proposed system have been discovered throughout this study. The relationship between the pressure exerted on PBB and resistance generated in the velostat is not linear. This means that there is only a range of pressures which has a linear relation of resistance which put limitations on the pressure which is allowed. The dataset is small in terms of the number of participants and the number of required presses per participant is only three. A more elaborative study should focus on the behavior of the braking system, especially outside the range of pressures which has a linear relation with resistance which put limitations on the pressure which is allowed. A larger dataset is required in terms of the number of participants and the number of required presses per participant which must increase especially in the nonlinear range. Also, the other parts of the system required to realize the whole proposed braking system, which is mentioned in section one, still need to be implemented and tested.

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