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论文题目：An AI-Based Ambulatory Ankle Brace with Wearable Sensor used for Preventing Ankle Sprains

An AI-Based Ambulatory Ankle Brace with Wearable Sensor used for Preventing Ankle Sprains

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Abstract

Ankle sprain is one of the most common injuries in the game of basketball. The ankle sprain may bring tremendous time and cost loss, and patients with a history of ankle sprain are susceptible to further ankle injuries. This paper proposes an AI-based ambulatory ankle brace with wearable sensors that can be used for ankle-sprain prevention. The equipment consists a sensor, a microcomputer, a Bluetooth module, and a muscle stimulator. Ten volunteers performed twelve basketball moves with the ankle brace on, and the twelve basketball moves were labeled as high-risk and low-risk. The sensor on the ankle brace measured the 3-dimensional angular velocity and angular displacement of the subject's ankle in real-time, and the data were then fed to different machine learning algorithms to create models to predict future ankle motions. The model with the best performance created by the Random Forest algorithm was imported into the microcomputer. Once the model predicts a high-risk move, the microcomputer sends a Bluetooth signal to the muscle stimulator. The one end of the stimulator is a pair of electrodes attached to the peroneal muscles to restrict ankle motion. When the stimulator receives the "high-risk" signal, it's activated and the spraining motion would be alleviated. In this way, the ankle brace doesn't restrict normal ankle movement while providing adequate protection for potential ankle sprain cases.

Keywords: ankle-sprain prevention, machine learning, wearable sensor, muscle stimulator.

CONTENTS

1 Introduction

Ankle sprain not only causes damage in the short term but also increases the risk of further ankle injuries. It's been reported that most patients who experienced ankle sprain are vulnerable to further ankle injuries[1], which can be described as "chronic ankle instability" (CAI). A previous study indicated that 28% of ankle sprain cases sustained during basketball were recurrent and 60 % of participants reporting an ankle sprain had sprained ankles more than once[2], which can be described as the symptoms of CAI. What's more, the CAI is related to the instability of peroneal muscles[3] that control the ankle motion.

Besides undermining patients' working ability, ankle sprains may bring tremendous cost loss. Although more validated and comprehensive estimations on ankle sprain's societal cost have to be made, previous studies showed that the social cost of ankle sprains in a population of British emergency department patients is £940 per case[4]. In the Netherlands, the costs of ankle sprain presenting at an ED are calculated to be €823 from when the ankle sprain occurs to the moment it recovers[5].

From short-term (medical spending) to long-term cost (the loss of working time), and from direct (lateral ankle sprain) to indirect damage (chronic ankle instability), ankle sprains have various effects on sporting populations as well as others. The ankle sprain is one of the most common injuries in indoor and court sports[6]. Even in the professional context, ankle sprains affect approximately 26% of NBA players on average each season and account for a large number of missed NBA games in aggregate. In some cases of high ankle sprain, players even missed 16 NBA games and took up to 37 days to recover from the injuries[7]. The games missed become especially crucial concerning the "playoffs" in NBA, where 16 teams strive for the final championship. If the most skillful player suffers a severe ankle sprain in the playoffs, his team is likely to miss the championship. Therefore, minimizing the risk of ankle sprains increases the chance for teams to win the championship.

To reduce the negative effects, researchers have found many ways to detect or protect people from such injuries. The identification and detection of ankle sprains have been explored much, and multifunctional sensors are used as a tool. Pressure sensors have been used on three crucial positions of the sole to detect the ankle sprain[8]. Some other researchers have used eight motion sensors with a tri-axial accelerometer and gyroscope to collect angle data to train a support vector machine for the identification of ankle sprains, and the angle sensor on the ankle that produces the highest signal strength is the one on the medial calcaneus[9].

To prevent ankle sprains, prophylactic equipment is recommended, because participants with a history of an ankle sprain are less likely to suffer ankle sprain again with such protection[10]. From the research, extra protection can make up for the instability (such as CAI) caused by previous injuries, and these protections include ankle braces, fibular re-position tape, and ankle taping. Other than passive protection, active correction is also explored. A semi-rigid brace can turn rigid immediately when it's stimulated, and thus reducing the angular velocity and controlling the angle of the ankle[11]. Another study utilized myoelectric stimulation for peroneal muscles to react to protect the ankle[12]. However, in previous ankle sprain prevention devices, models and thresholds for predicting sprains were largely empirically established, which made sprain predictions occasionally misjudged. This study established a threshold to identify ankle sprains, and its method of using myoelectric stimulation for peroneal muscle is eligible because the muscle can be stimulated to react faster (about 25ms) to prevent ankle sprain (usually occurs in 50ms). Most methods of muscle stimulation take about 60ms.

The objective of this study is to invent an AI-based ambulatory ankle brace for ankle sprain prevention. A sensor with an accelerometer and gyroscope is used on the medial calcaneus of the foot to monitor the user's ankle movement. The data collected by the sensor is sent to cellphones through Bluetooth and is recorded. Then the data sets are fed to machine learning algorithms to create predictive models that can identify the risk level of different basketball moves with respect to ankle sprain injuries. The best-performed model is integrated to the micro-controller program. If the model identifies high-risk cases, it sends a message through the Bluetooth module to activate TenS (Transcutaneous Electrical Nerve Stimulator) stimulator. The TenS stimulator attached on the peroneal muscle emits neuro-muscular electrical stimulation that stimulates the muscles to contract to resist the sprain. Altogether, an ankle brace with both detective and protective functions is developed. Models predicted by machine learning methods have many advantages over ones derived from empirical modeling. For example, the prediction model is more accurate with the support of a large amount of data. The data is continuously recorded and imported, and the model will be optimized to be more accurate. The accuracy of the model will make the prediction of ankle sprain more accurate and prevent misjudgment.

2 Method

2.1 Characteristics of Hardware

The ankle brace consists of five essential parts (as Figure 1. shown): a Micro- Electro-Mechanic System (MEMS) sensor, Bluetooth modules, a single-chip microcomputer, a power source, and a muscle stimulator.

1）The sensor is a JY-61 sensor with a 3-axial gyroscope and 3-axial accelerometer that was developed based on Micro-Electro-Mechanic System (Wit-Motion, Shenzhen, China).

2）Bluetooth modules are HC-06 with a working frequency of 2.4GHZ.

3）For the single-chip microcomputer, Nano V3.0 ATMEGA168P is used. ATMEGA168P is a low-power CMOS8 - bit microcontroller based on AVR. It has an enhanced RISC architecture. By executing powerful instructions in a single clock cycle, throughput close to MHz1MIPS is achieved, allowing system designers to optimize power consumption and processing speed. The AVR kernel combines a rich instruction set with 32 general-purpose working registers. All 32 registers are directly connected to the Arithmetic Logic Unit (ALU), allowing access to two independent registers in a single instruction executed in a clock cycle. The resulting architecture achieves throughput up to ten times faster than traditional CISC microcontrollers while achieving higher code efficiency. The AI algorithm requires high computational power, and this MCU supports the operational computational power requirements of the AI algorithm.

4）The power of the device is provided by Philips battery with a voltage of 9V.

5）The muscle stimulator is the TenS, a neuro-muscular electrical stimulation that stimulates a group of muscles to make them contract using the current at the frequency of 20-50Hz.

2.2 Arrangement of Hardware

The JY-61 sensor and the Bluetooth module are connected to the microcomputer with a movable power source. The sensor collects and sends the data at a frequency of 15 Hz, then the data are sent through the Bluetooth to experimenter's mobile phone.

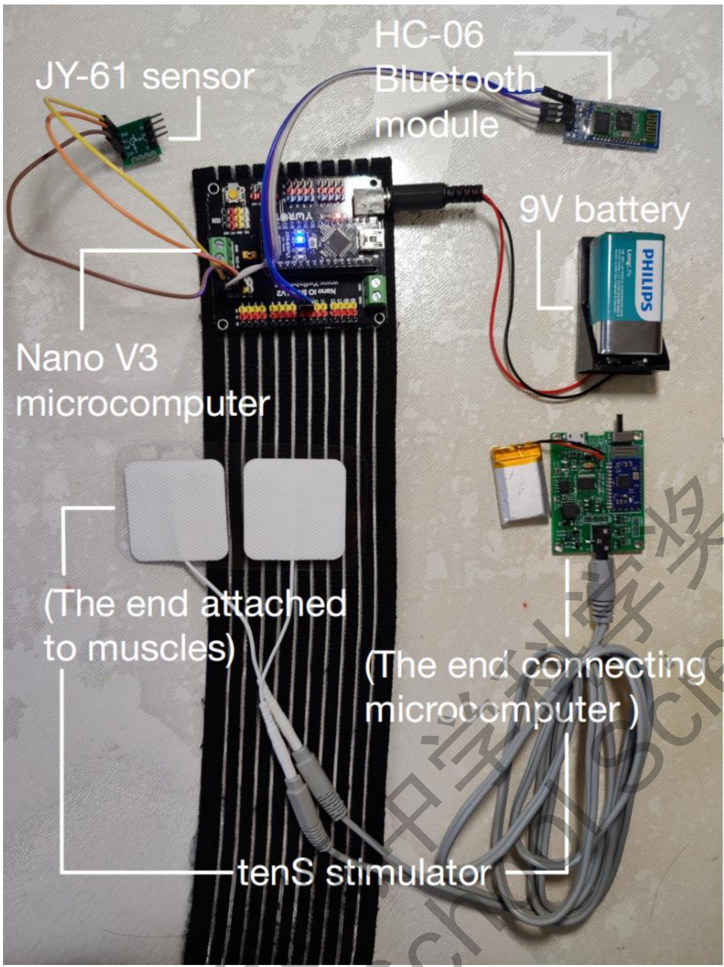

Figure 1. The components of the device

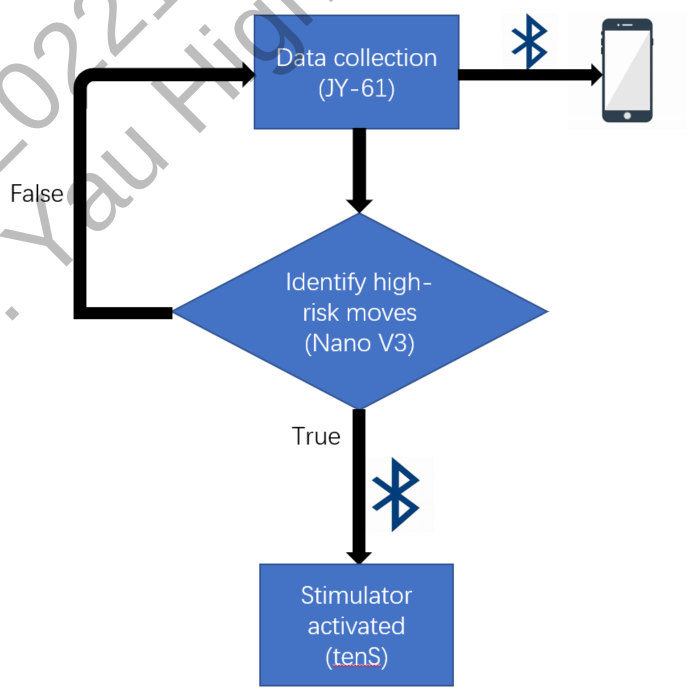

Figure 2. The flow chart of the device

The JY-61 sensor is located on the medial calcaneus of the foot. According to previous research on the signal strength of the sensors on different locations of the foot, the sensor on medial calcaneus had the highest signal strength [9]. The one end of the TenS stimulator is attached to the peroneal muscles for effective muscle stimulation [7].

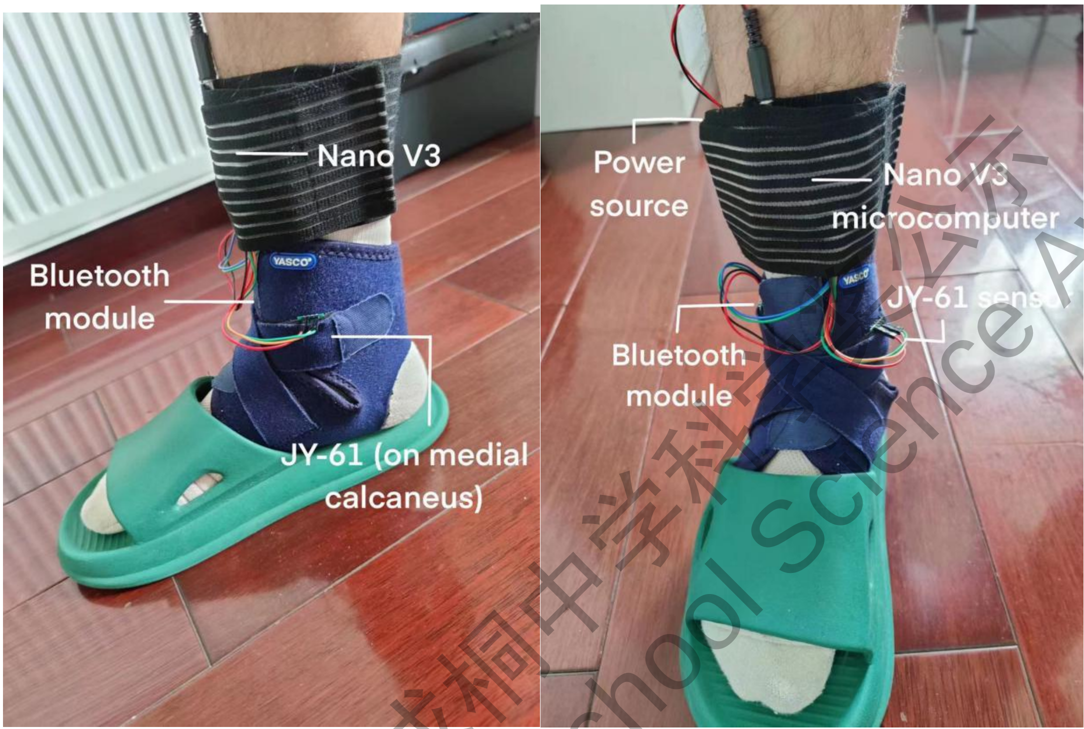

Figure 3. The arrangement of the hardware

2.3 Subjects

Ten male high school students (age = 16yrs, height = 178.8cm, body mass = 74.96kg) were recruited. All of them have some experience of basketball playing. All the subjects were provided with project protocols before the experiment, and the experimenter received all of their consent.

2.4 Experiment design

Ten volunteers were assigned to perform twelve basketball movements in total, each for ten times. The basketball moves were separated based on the categories of "finishing" (6 moves) and "dribbling" (6 moves), and each move has been previously labeled with "high risk" or "low risk".

2.4.1 List of basketball moves

The list and risk level of the basketball moves was concluded based on the empirical evidence given by my varsity team basketball coach and teammates.

TABLE 1. The list of basketball moves

	High-risk	Low-risk
Finishing	Non-contact double pump	Floater
	Euro step	Finger roll
	Fade-away shot	Reverse Layup
Dribbling	Shot fake and drop pivot	Drag Step
	Hang leg and go	Post Spin
	Drop and go	Under drag

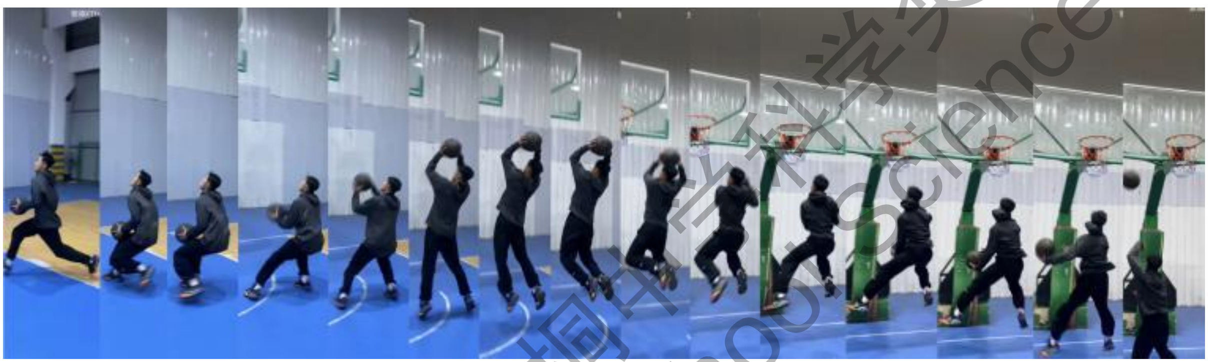

Figure 4.1. The basketball move: non-contact double pump[1]

Figure 4.2. The basketball move: euro step [2]

[1] 邹涵 XTtexun, (2022-05-08), "只需三步轻松学会拉杆上篮！ ", China, https://www.bilibili.com/video/BV1cL4y1F7Xx?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

[2] 野球帝, (2019-05-14), "教你如何练好欧洲步！ ", China, https://www.bilibili.com/video/BV1R4411a7UD?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

Figure 4.3. The basketball move: fade-away shot[3]

Figure 4.4. The basketball move: floater[4]

Figure 4.5. The basketball move: finger roll[5]

[3] 野球帝王师傅, (2020-05-17), "后仰跳投怎么练", China, https://www.bilibili.com/video/BV1854y1X7fB?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

[4] MicahLancaster 迈卡,(2021-05-29), "练抛投", China, https://www.bilibili.com/video/BV1f44y1r7UY?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

[5] 初心刘师傅, (2022-04-04)"比扣篮还飘逸的"挑篮教程"三个练习丨轻松学会飘逸的挑篮, 让你成为球场最亮的仔！", China, https://www.bilibili.com/video/BV1BY41177Cw?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

Figure 4.6. The basketball move: reverse layup[6]

[6] Balls-is-love, (2020-04-06), "【篮球教学】【反身上篮教学】", China, https://www.bilibili.com/video/BV1DK411L7u4?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

Figure 4.7. The basketball move: shot fake and drop pivot[7]

Figure 4.8. The basketball move: hang leg and go[8]

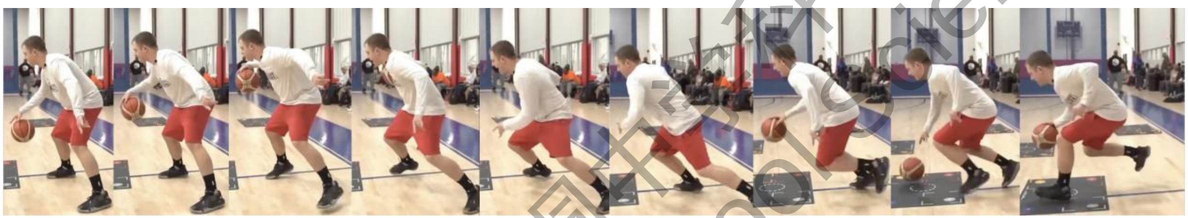

Figure 4.9. The basketball move: drop and go[9]

Figure 4.10. The basketball move: drag step[10]

7 隐藏宝石 HiddenGems, (2021-07-03), "Negative Step 后蹬步解析 迅速提高你的启动速度 美式单挑必备技能 职业球员常用突破技术【宝石碎片 GemPieces Vol.71】", China, https://www.bilibili.com/video/BV1s44y1q7ag?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

8 李观洋, (2020-05-29), (2020-05-29), "剪刀步的几个细节！", China, https://www.bilibili.com/video/BV13K411s77G?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

9 MicahLancaster 迈卡, (2020-11-12), "坠步的威力", China, https://www.bilibili.com/video/BV1Ga411w7bZ?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

10 邹涵 XTtexun, (2022-08-01), "《拖曳步》的脚步细节你做对了吗？", China, https://www.bilibili.com/video/BV1hV4y1j7QL?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

Figure 4.11. The basketball move: post spin[11]

Figure 4.12. The basketball move: under drag[12]

2.4.2 Experimental Procedure

Participants were instructed to review certain moves from the instructive videos I selected on Bilibili video website. After 5 minutes of learning time, they put on the ambulatory ankle brace. Before they started performing, a research staff with knowledge of the motion sensor checked the stability of the equipment and the accuracy of the sensor while the participant kept still. Then each volunteer followed the instructions to start performing. Each move needed to be performed 10 times, and there were 10 seconds for static poses between each move in order to distinguish the trials. Between each move (10 trials for each), the participant was allowed to take 3-minute rest to have better performance.

2.5 Data Processing

2.5.1 Data Extraction

HC-06 Bluetooth module sent data continuously without any pause, so I extracted the data representing the volunteer's moving status from those representing static pose based on the dynamic changes in x-axis gyroscope. According to the examination, a change that exceeds a value of 20 in x-axis gyroscope (unitless) represents the start of one move.

[11] 路人王篮球, (2021-08-27), "【纯干货】零基础后转身过人", China, https://www.bilibili.com/video/BV1bh411W7UM?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

[12] 邹涵 XTtexun, (2022-06-10), "学会这招反胯下拉回, 让你的突破更有侵略性！ ", China, https://www.bilibili.com/video/BV1WY4y1G7AZ?spm_id_from=333.999.0.0&vd_source=e8c84153d6e6bddc60e54a19541e2da6

2.5.2 Data Feature

The three-dimension angular velocity and angular displacement are converted into one-dimensional vectors using the two equations below.

$$\|\theta\| = \sqrt{\theta_x^{\ 2} + \theta_y^2 + \theta_z^2} \tag{1}$$

$$\mathrm{a}_{total} = \sqrt{a_x^2 + a_y^2 + a_z^2} \tag{2}$$

Then I calculated the minimum, median, mean, standard deviation, and maximum of each angular velocity and displacement vector. The skewness and kurtosis are also represented by unitless values. Skewness is a statistical term used to estimate the shape of the data distribution: if the value > 0, then there's more weight in the left tail of the distribution; if the value < 0, then there's more weight in the right tail of the distribution. Kurtosis is a statistical term used to estimate the shape of the data distribution, for distribution with kurtosis value < 3, it is platykurtic; for distribution with kurtosis value > 3, it is leptokurtic.

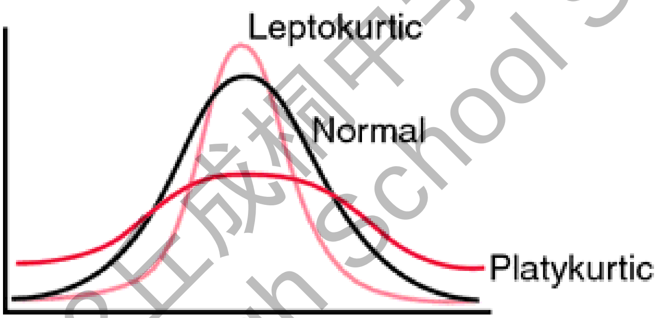

Figure 5. The kurtosis of a distribution. The Free Dictionary, https://medical-dictionary.thefreedictionary.com/Platykurtic+distribution)

2.5.3 Data Importing

Two lists were imported to the training model: X is the list of data features, and Y is a list of the risk level. The dimension of X is 1200*64, where 1200 means that 12 volunteers are performing 10 moves, each for 10 times (12*10*10 moves); where 64 means that for each time of the move, there are 64 features in total, including mean, standard deviation, minimum, median, maximum, skewness, kurtosis, and interval (8 features) under 8 categories: angular velocity in x, y, z dimensions; net angular velocity; angular displacement in x, y, z dimensions; and net angular displacement (8*8 features).

In the list Y, high-risk basketball moves were labeled with 1, and low-risk moves were labeled with 0.

Then, the "train_test_split" function was used to randomly split the whole data sets into training and testing sets. The testing size was set as 0.2.

2.5.4 Data Standardization

Data standardization is a common requirement for many machine learning estimators, and it can unify different data into a standard format. It requires removing the mean and scaling to unit variance by using the following equation:

$$z = (x - u) / s \tag{3}$$

The z, x, u, and s represent: standard score (z-score), one feature in the sample, the mean of the sample, and the standard deviation of the sample. Initially, the training set was assigned as the object of the function StandardScaler(), and then I used fit_transform() to transform and standardize both the training and testing set.

2.6 Machine Learning

To distinguish between high-risk and low-risk basketball moves, three different machine learning algorithms were used to create models. After I created models with the training set, the testing set was used to evaluate the performance of the models for later comparison. Therefore, the relatively most effective model for my classification problem was found. The workflow is as presented:

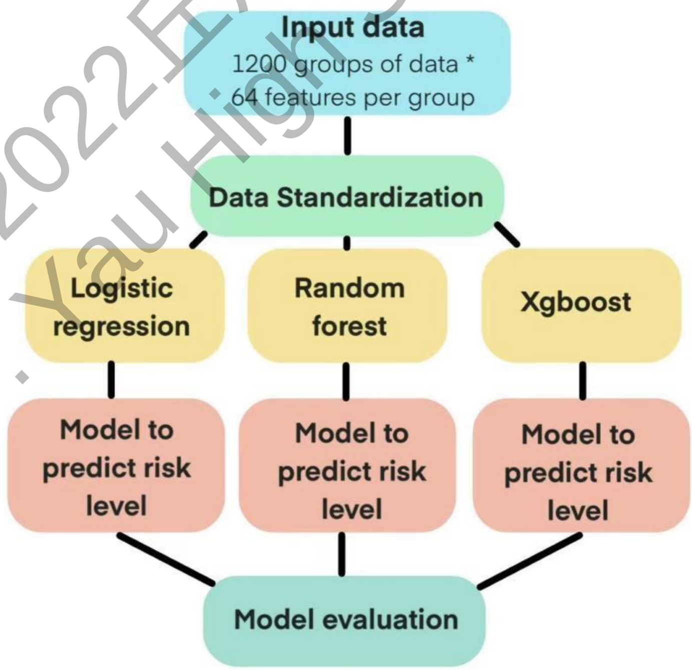

Figure 6. The workflow of machine learning

2.6.1 Algorithm 1: Logistic Regression

Logistic regression is a supervised machine learning algorithm, and it's also a discriminative model that can be used for classification problems. It allows the analysis of "dichotomous or binary outcomes with 2 mutually exclusive levels"[13], such as the "low-risk" and "high-risk" in my case.

I imported Logistic Regression from Scikit-learn in python and created a model using the training set.

2.6.2 Algorithm 2: Random Forest

Random forest is a supervised machine learning algorithm, which means that my final model is created by a training dataset with certain labels. The model would learn from the training set and its label in order to predict future data [14]. Random forest is an ensemble composed of multiple decision trees, and the tree resembles a flow chart with multiple conditions and two pathways ("yes" or "no"), working based on the if-then-else rule. The decision trees in random forest are trained with the "bagging" method, which reduces the variance (an error that makes the model too sensitive to noise) in high variance algorithms like decision tree.

Each tree would generate one result, and finally, the algorithm would identify the most frequent classification result of the decision tree as the final result.

2.6.3 Algorithm 3: Xgboost

Xgboost is a scalable extreme gradient boosting method that's widely used by data scientists to provide state-of-the-art data[15]. Similar to random forest, xgboost is also a decision tree ensemble algorithm, but the difference is how trees are built and combined.

3 Results

TABLE 2. Performance evaluation values

	AUC	Accuracy	Recall	Precision	F1-Score
Random Forest	0.828	0.723	0.689	0.739	0.713
Logistic Regression	0.727	0.668	0.664	0.669	0.667
Xgboost	0.818	0.718	0.714	0.720	0.717

After the testing set was applied to evaluate the model's performance, five performance evaluation values shown in table 2 were given. The label of data is either positive (high-risk) or negative (low-risk). All values below were calculated using the elements from the confusion matrix.

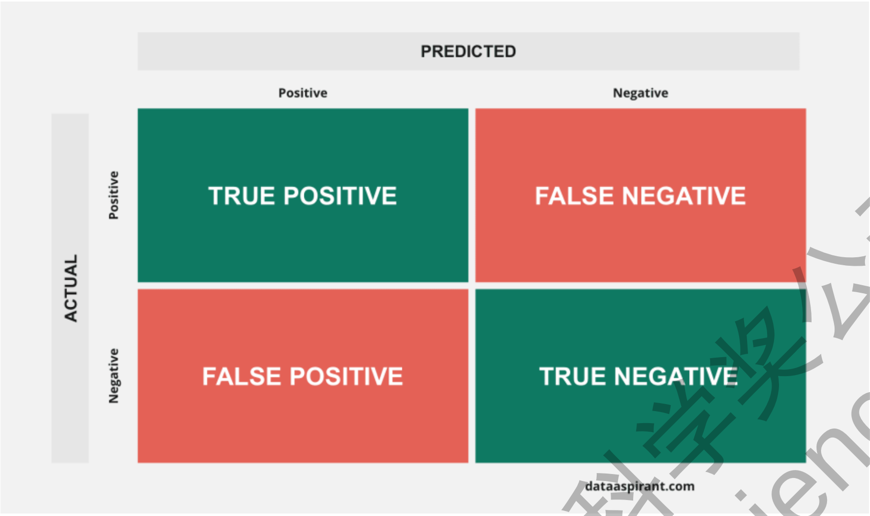

Figure 7. Confusion matrix. (Confusion matrix, https://dataaspirant.com/3_confusion_matrix/)

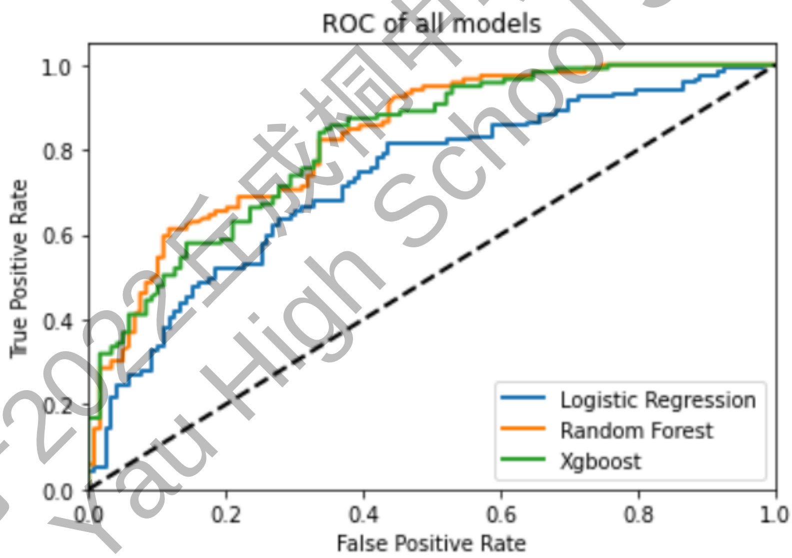

Figure 8. ROC curves for three models

Accuracy: accuracy shows the model's performance in making correct predictions, and it's calculated using the equation below:

$$Accuracy = Correct\ predictions\ /\ All\ predictions \tag{4}$$

Recall: recall, also known as "sensitivity", is a performance metric that shows the correctly identified positive among all data supposed to be positive. The equation is:

$$Recall = TP\left(true\ positive\right) / \left[TP\ \left(true\ positive\right) + FN\left(\ false\ negative\right)\right] \tag{5}$$

The false negative belongs to the positive class because it's falsely identified as the opposite.

Precision: precision is the proportion of correct positive data out of all positive data (including false positive). It can be calculated by:

$$Precision = TP\ (true\ positive) / TP(true\ positive) + FP(\ false\ positive) \tag{6}$$

F1-Score: f1-score gives the combined information of accuracy and precision, or it can be interpreted as the weighted average. It ranges from 0 to 1, and the higher the value is the better performance the model has.

As Table 2. shown, the model of random forest algorithm performs the best relatively, since it has the highest value of AUC (0.828), accuracy (0.723), and precision (0.739). However, the model of xgboost algorithm has the highest recall value (0.714), and the recall value affects its f1-score, resulting in the highest f1-score (0.717) as well.

4 Discussion

Among various AI algorithms, the above three algorithms are chosen because each of them has some unique advantages, and there are also trade-offs in the use of these three methods in this study:

1. Logistic regression. Using logistic regression, I can know that under certain conditions, how possible the move can be high-risk. However, the algorithm is prone to overfitting, particularly when there are many variables from the data.

2. Random Forest. The identification of risk level is a classification problem, and random forest performs well in classification. Its bagging method works to decrease the bias. The feature of imported data is also high-dimensional (with 64 values for each), and this algorithm doesn't need dimension reduction when facing data with the high-dimensional features. Furthermore, when I was collecting the data, there wasn't an ideal laboratory environment, so there was more or less noise in the data, but random forest algorithm is not easily overfitted. However, the training time and storage can be disadvantages as the number of trees increases.

3. Xgboost. Xgboost sets a targeted outcome for next model, and the targeted outcome comes from the difference (gradient) between the error and the predicted value, so the algorithm usually generates high accuracy. But because it's constantly decreasing the gradient with the next model, the algorithm is sensitive to outliers.

As my result shown, random forest and xgboost algorithms are relatively ideal for our classification problem. For the most evaluations, random forest generates a more precise result, so it can be still used in further experiments; at the same time, xgboost has a higher value of recall, which is of great significance in my project. Higher recall means a higher chance for high-risk cases to be identified. My project aims at preventing the ankle from spraining, so high recall is crucial for the model used in my project.

The project creates an ankle brace device that can actively prevent ankle sprains. The identification of high risk is reliable because three different machine learning models trained with 1200 data sets were compared and filtered. The advantages of the device are apparent: 1) the cost of each component is low compared to other ankle protective equipment; 2) with large amount of training, the machine learning can effectively find the pattern of high-risk moves that cause ankle sprain; 3) more intense protection can only be activated when there's potentially an ankle sprain case, so it exerts no restriction for the user's normal movement.

In the final stage, the model by random forest algorithm was imported to use and the microcomputer was programmed to detect high-risk moves, then TenS stimulator was activated. When I was performing high-risk moves, the TenS often worked, and I could feel the flow of current around my muscle to resist the motion, but the protection didn't happen all the time. It might be because of the error rate or the delay of the Bluetooth device. Thus, this project can still be improved. For later studies, larger data sets can be fed, because the large sample size significantly lowers the error rates[14], and it's likely to improve the recall. Other randomness can also be injected to random forest and xgboost algorithms. More machine learning algorithms can be employed to create models and the performance may even be further improved. Furthermore, connection using wire might be more effective than the signal emitted by Bluetooth module. In addition, the list and label of the basketball moves can be improved as well. They were concluded based on the empirical evidence provided by the head coach and teammates from my varsity team, so the criteria for high-risk level might be diverse. More research can be done on the prevalence of different basketball moves from the game, and the risk level of the move can be determined by previously reported injury cases in other locations.

5 Conclusion

This project develops a protective ankle brace that can be used to lower the rate of ankle sprain given the consequence of this injury. The application of AI method improved the effectiveness and accuracy of detection for high-risk moves. The activation mechanism of TenS stimulator lowers the restriction for normal ankle movement, since TenS only provides protection in high-risk cases.

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Acknowledgment

I've been dedicated to basketball for 7 years. Like most basketball athletes, my passion has never declined, no matter how much sweat and tear it costs or how aggressive my opponents are. Nevertheless, there are countless contacts and unpredictable situations during basketball games, and injuries we encountered inevitably segregate us from chasing our dream. The most common basketball injury is the ankle sprain, and in fact, my left ankle is suffering the sprain injury when I'm writing this acknowledgment. Furthermore, besides in the context of basketball, people who have ankle sprain experiences are more likely to suffer again, and so do the elderly who have lost their ankle stability. The extreme pain I've been experiencing and the tremendously serious outcomes I learned from literature review motivated me to start this ambulatory ankle brace project to both effectively identify high-risk basketball movements and to potentially prevent injuries.

I would like to put my gratitude toward my parents in the first place. I could not devote myself to basketball without their full support, since they've never stopped encouraging me to set a higher goal in basketball, from school team to varsity, or even dreaming to be a professional athlete. Growing up, I have always been told by my parents to be a pro-social person, and when I was repeatedly encountering ankle injuries, they helped me to overcome the depression and inspired me to research to prevent this injury.

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