GymSense: Exploration in Measuring Bench Press Form Using Sensor Technology

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***Abstract*—Proper weightlifting form is essential to prevent injuries, particularly for beginners. Our GymSense project is a computer system that monitors and provides feedback on critical aspects of form during the bench press exercise, including grip width, shoulder distance, shoulder abduction angle, tilt, and back arch. The system employs force and camera sensors, ArUco markers, and the BlazePose algorithm to measure the key parameters of form and provides feedback to the user during and after each set. The feedback loop allows users to identify areas for improvement and reduce the risk of injury. We conducted a user study to assess the accuracy of the first iteration of the system. We found through the user study that our system is not as accurate as a personal trainer, but our project presents the initial phase of an alternative approach for obtaining feedback on a user's bench press form.**

I. Introduction

A. Bench Press Form and Injury

As weight training becomes more analytical with technology, the ability to assess various aspects of a lift can be created to inform and aid novice weightlifters to improve their form and reduce injury. The creation of Gymsoles, a system used to find the force of center of pressure while performing exercises such as the squat and deadlift can help provide feedback to execute the lift [1]. When looking at similar systems for another lift, the bench press, there were limited tools to analyze the parameters of a bench press. The correct execution of exercises is essential to prevent various bodily injuries. The bench press is commonly associated with upper body injuries. A recent cross-sectional study titled "Prevalence and Consequences of Injuries in Powerlifting" found that the bench press accounted for 27% of all injuries and 56% of shoulder injuries reported by powerlifters in the study [2].

The book "Proper Bench Press Form" by Nicholas Gallo, a Physical Therapist, and a Doctor of Physical Therapy, provided the team with a list of parameters necessary for proper bench press execution, including bench press consist of balanced bar, proper elbow placement, proper grip width, proper forearm placement, activated shoulders, a straight bar path, proper wrist placement, proper breathing technique, an arched back, activated glutes, and contact with the ground [3]. With the aid of sensors, the ability to give feedback on the measurement of these parameters can be possible.

B. Sensor Feedback and Changes in Form

When considering parameters, we consult certified personal trainers, gym owners, members of the James Madison University powerlifting club, and conduct our own research. We have these stakeholders rank the importance of the parameters while as a team, we rank both the feasibility and importance of measuring the parameters in the system. This is done to prioritize the parameters that are the most beneficial to the user's form. As a team, we prioritize the user's safety, comfort, and overall experience by focusing on finding non-intrusive methods of detection. To achieve this goal, we conduct extensive research on various sensors and measurement techniques that can be integrated into the system to accurately detect the chosen parameters, and we are unable to identify non-intrusive methods of detecting the specific parameters of wrist angle, forearm placement, glute activation, engagement of shoulders, and breathing during the exercise. For example, to measure if the glutes of the user are engaged requires more than just a force sensor as there is a difference in the glutes being in contact with the bench and in the act of contraction to support the trunk muscles to provide support for the spine and pelvis [4]. This requires a surface electromyography (sEMG) [5] or mechanomyography (MMG) sensor attached to the skin to measure the electric signals generated by the muscle [6]. This leads to the parameters chosen for this study consisting of shoulder abduction angle, bar tilt angle, grip width, shoulder distance, and back arch.

The use of cameras for sensing various parameters is made possible by the availability of different programs and libraries created in Python and supplemental materials. Positional data can be detected using the OpenCV [7] and the ArUco [8] library, which can provide feedback on the measurements of the tilt angle of the barbell and grip width. OpenCV is an open-source library that provides algorithms and tools for video processing

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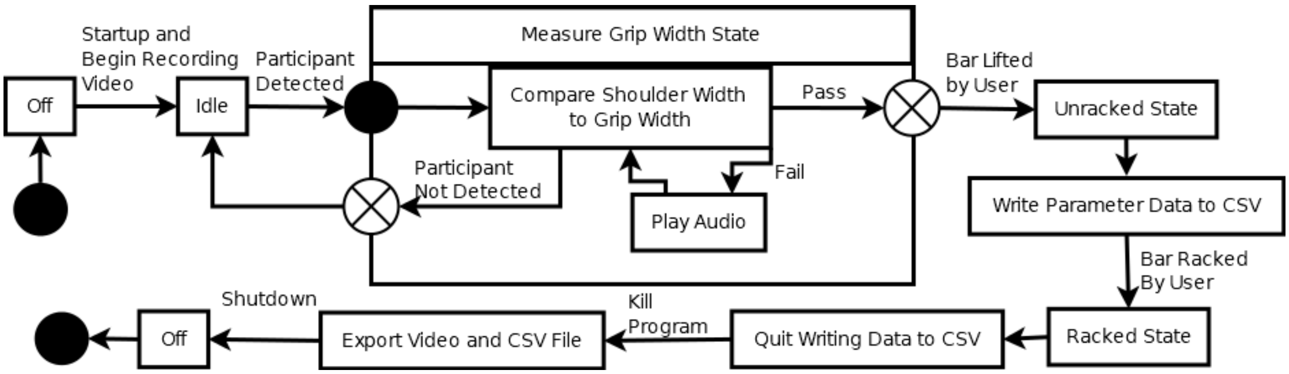

Fig. 1: State Machine Diagram of the System Algorithm

and object detection. ArUco is a module in OpenCV that provides markers with unique identification codes that can be detected and tracked by a camera. Using the BlazePose algorithm in Python and cameras, different landmarks on the body can be sensed, and calculations can be derived to find the angles in the body and the distance between different landmarks. Force sensors can be utilized as a tool to initiate the algorithm by racking or un-racking the barbell and can also be utilized to detect contact or non-contact for specific parts of the body, such as an arched back.

The GymSense system aims to provide feedback for improved technique and reduce the risk of injury in the bench press exercise. The system also provides concurrent and terminal feedback and coaching to help users correct any errors in their form, gain a better understanding of proper weightlifting technique, and achieve their personal fitness goals or future coaching opportunities.

The remainder of this paper is organized as follows: Section II discusses the key parameters used with the sensors in the study and provides an algorithm for detecting them. Section III outlines a user study to collect data from sensors with feedback from each parameter, while using verification methods with a personal trainer to check the accuracy of the system. Results from this study will be presented in Section IV, and Section V will emphasize the key findings from the system compared to an expert. Finally, in Section VI, we include a summary of the process, key findings, and future improvements.

II. Methodology and Approach

In this section, we describe the parameters of shoulder distance, shoulder abduction angle, grip width, tilt angle and back arch with the use of BlazePose, ArUco Markers, Open CV, and force sensors. Also, we provide an algorithm that lets us automatically determine the values of parameters and how feedback is given.

A. System Overview

A state machine model plays a crucial role in describing the behavior of a system using its set of states, events, and transitions. The model comprises several states that represent different conditions and modes that the system can be in, events that trigger transitions from one state to another, and transitions that dictate how the system moves from one state to another based on the events that occur. Utilizing this model, we can effectively communicate our system model and make the abstract algorithm more accessible to follow, as depicted in Figure 1. The state machine diagram begins in an off state until it is turned on, after which it enters an idle state until the ArUco markers worn by the user are detected by the camera. Our system measures the user's grip width relative to their shoulder width and generates audio cues to prompt the user to adjust their grip width if it falls outside the optimal range of 1.5 to 2 times the shoulder width. The system only provides feedback on the grip width immediately before the user lifts the bar off the rack. The system then repeats this until the user's grip width is within the proper parameters. Once the grip width is correct, the user is instructed to lift the bar, and data collection begins. Data collection is governed by the racked and un-racked states of the barbell. The force sensor detects the barbell on the rack as racked, and no data collection occurs. Once the force sensor on the barbell rack does not detect the barbell, data collection immediately begins since the system is in the un-racked state. After ten repetitions of the bench press exercise, the user racks the bar, and the system exports the video and CSV files. The system is now idle until it is restarted. To ensure safety, we offer terminal feedback on specific parameters upon completion of the exercise, including left shoulder abduction angle, right shoulder abduction angle, back arch, and tilt of the bar. This feedback is terminal to prevent potential injuries to the user during the exercise.

B. BlazePose Modeling and Calculations

Figure 2 depicts the Pose Landmark Model, which utilizes a machine learning algorithm to track body pose. This model can identify 33 distinct landmarks on the body, some of which are used to detect parameters in the algorithm. Specifically, landmarks 11 and 12 are used to determine the distance between the shoulders, while landmarks 14, 12, and 24 are used to detect the angle between the right elbow and the right hip, and landmarks

13, 11, and 23 are used to detect the angle between the left elbow and the left hip. During discussions with experts, it was found to be important to ensure that the grip width of each hand was between 1.5 to 2 times the distance between the shoulders to prevent the elbows from being tucked in if the grip width was too close or flared out if it was too wide [9]. The proper shoulder abduction angle for this range is between 45 – 70 degrees, which can be detected using these landmarks [10].

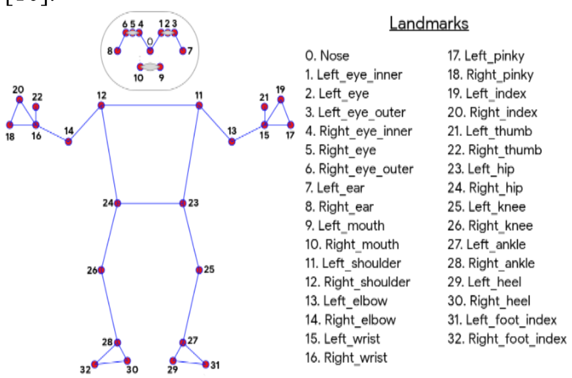

Fig. 2: Pose Landmark Model with numbers corresponding to the part of the body [11]

To determine the user's shoulder width, the x and y-coordinates of each shoulder were transformed from camera space coordinates to centimeters. Since the user is consistently six feet away from the camera, the x and y-coordinate data are uniform. After identifying the positional data of each shoulder, the Euclidean distance between the two points is calculated to find the user's shoulder width. The shoulder abduction angle is identified by computing the hip-to-shoulder-to-elbow angle using the positional data obtained from the corresponding landmarks.

C. ArUco Marker Modeling & Calculation

Figure 3 is an ArUco marker, which is an augmented reality marker that allows the detection of the X, Y, and Z axis. ArUco markers can be paired with an OpenCV library and camera sensors that allow real-time tracking of the positional data of these markers. This data is important when considering the distance between two markers to determine the grip width of the user, and finding the angle from one ArUco marker to the other to determine if there is a tilt from one end of the bar to the other. It is important to note that an uneven bar can cause injury and puts more of a load distribution on one side of the body, therefore finding that no more than two degrees was an acceptable angle for tilt of the bar [12]. The user's gloves are affixed with ArUco markers bearing different IDs. These markers are detected using a camera, allowing the program to determine the 3D location of each marker relative to the camera. By calculating the Euclidean distance between the two markers, the program can derive the user's grip width. The grip width is compared to the user's shoulder width to determine whether their grip width is within the ideal range.

Fig. 3: ArUco Markers on gloves to track grip width

D. Force Sensor Modeling and Calculation

The back arch parameter is crucial for increasing shoulder stability during the bench press exercise, especially since the shoulder is a ball-and-socked joint that can naturally handle less stress. Arching the back locks the ball of the shoulder deeper into the socket, resulting in greater stability compared to benching without an arch [13]. However, novice lifters are often not taught this vital parameter, as it only becomes relevant once the weight of a barbell increases. Consequently, it is mostly experts and powerlifters that arch their back. Nonetheless, it remains an essential parameter for proper bench press form. By employing force sensors to measure back contact, the system can detect whether the user is arching their back during the lift or keeping it flat on the bench. Two force sensors are connected to the Arduino, with one placed on the barbell rack to detect the rack state of the barbell, and the other used to identify any arching of the user's back. To start the system, we implement a force sensor on the rack of the barbell to capture when the bar is being lifted off. Upon detecting the barbell being un-racked, data for all parameters is written into a CSV file, with the program ceasing to write data once the barbell is re-racked.

III. User Study and Experimental Design

A. User Interaction

A user study approved by IRB#23-4097 was conducted to test the efficacy of the algorithm in our system in measuring key parameters and given feedback as stated in Section II amongst an expert evaluation. The study was held in a classroom in the Engineering and Geosciences building where thirteen healthy young adults were recruited to participate. Two desired barbell weights, a 2-lb broomstick handle or a 14-lb barbell, are presented to choose from to complete ten repetitions of the bench press exercise. The option was given to switch out barbells at any time, and if uncertain, the user can begin with the 2-lb broomstick handle. Afterward, the user was then shown a video that taught the user how to perform the exercise. After watching the video and asking any questions or concerns, the user was instructed to put on a pair of gloves with ArUco markers attached. To calibrate with their bodily parameters, the user is instructed to lay down on the bench. One investigator is designated as a spotter for the user and constantly watches to ensure no injuries occur and will be active on the side so that the video sensors can capture data. Concurrent feedback by audio cues is given when the users hands are on the bar, letting them know when they are within the ideal range. The user then performs up to ten repetitions of the bench press exercise with a focus on proper form. If the user's form is bad enough to cause injury, exercising is immediately stopped by the investigators and the user is then given corrective feedback before restarting the exercise if they feel comfortable. After the set is finished, the system produces an overall summary of feedback for each parameter about how the user performed. The data saved include CSV files that record the overall parameters and video data that captures the user performing the bench press exercise.

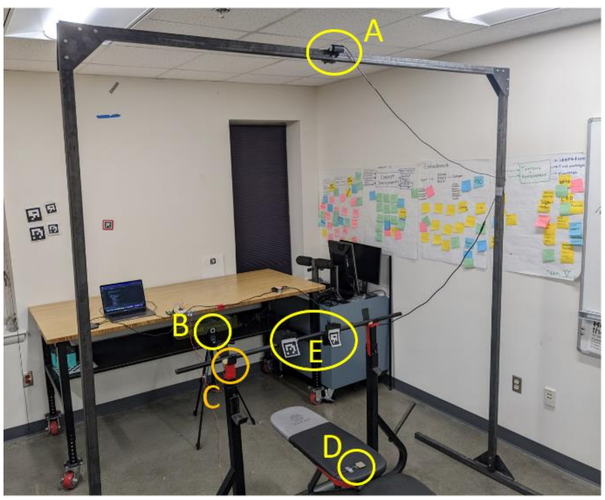

Fig. 4: Image of System. A is the BlazePose Camera. B is the AruCo Marker Camera. C is the Rack Force Sensor. D is the Arched Back Force Sensor. E are the AruCo Marker on the Gloves.

B. Expert Evaluation/Validation

The video data was given to a certified personal trainer to identify the validity of the algorithm in the system. The personal trainer was given the recorded videos and the list of key parameters to look at per data set. The personal trainer looked at each repetition per data set and listed their feedback for each parameter. The videos were marked with a Unix timestamp which was also captured in the CSV data that was recorded. After receiving feedback from the expert for each user's individual repetition, the investigators had the opportunity to look at both human feedback and the algorithm feedback of the system. The bench press exercise has two motions, the eccentric motion where the bar path travels down to the chest and the concentric motion, where the bar path goes to its apex. To compare the two feedbacks, we identified the time where the user is at the maximum eccentric motion of their repetition and used the corresponding data recorded at that time. This allowed for a comparison of the parameters of correctness with that of a human expert, which will help refine the system and demonstrate its accuracy in detecting from failure.

IV. Results

The results were derived by the discretion of one expert's feedback to the thirteen data sets against the systems feedback detection method. This was done using the binary classification where we were able to find true positive (TP), true negative (TN), false positive (FP) and false negatives (FN) per each parameter. When both the expert and system detected that the parameter had correct form, that would be considered a TP. When both the expert and system detected there was an error in the parameter, this would be considered a TN. When the expert determined an error in the parameter, but the system detected that the parameter had no error, that was considered a FP. When the Expert determined the parameter had no error, but our system detected an error, this was considered a FN.

As seen in Table 1, the total number of TP, TN, FP and FN were recorded for each parameter, Arch, Grip Width, Left Angle, Right Angle and Tilt. There were a total of 125 reps recorded per parameter, and there were a total of 322 TP results recorded and 129 TN recorded. There were also 77 FP results and 97 FN results recorded. The total number of repetitions recorded was 625 among the thirteen different data sets as seen in Table 1.

Table 1: The amount of TP, TN, FP, FN from the parameters measured by the system compared with an expert

	Arch	**Grip Width**	**Left Angle**	**Right Angle**	**Tilt**	**Total**
TP	101	100	20	34	67	322
TN	0	0	87	32	10	129
FP	20	8	5	9	35	77
FN	4	17	13	50	13	97
Total	125	125	125	125	125	**625**

To assess the accuracy of the system, the team seeks feedback from experts and uses an equation in which accuracy is expressed as a percentage. The equation involves adding the total number of True Positives to the total number of True Negatives and dividing the sum by the total number of results recorded in the table. The team calculates the accuracy for each parameter individually, as well as the accuracy of the total classifications obtained by aggregating all results.

Table 2: Accuracy of each individual parameter and accuracy of the system as a whole

	Arch	Grip Width	Left Angle	Right Angle	Tilt	Total
Accuracy	80.80 %	80.00 %	85.60 %	52.80 %	61.60 %	72.16 %

The accuracy recorded shows that the left angle was measured most accurately at 85.60% followed by Arch at 80.80% and Grip width at 80.00% as seen in Table 2. The accuracy of the right angle was the least accurate at 52.80% accurate and that was followed by tilt being 61.60% accurate. The total number of TP, TN, FP, and FN were also taken amongst the entire system and when finding the accuracy of the system based on all parameters, the system detected accuracy at a percentage of 72.16%.

V. Discussion

A. *Results Discusion*

When considering the accuracy of our entire system, we saw that our system and the expert were able to detect 322 True Positives and 129 True Negatives. This showed that within the 625 total possible outcomes, the system was 72.16% accurate. Our system's function was to serve the purpose of aiding novice lifters improve their form by giving them feedback on their bench press parameters. Given that our overall system error was 27.84% this system is not safe for novice lifters to rely solely on to improve their form as there are discrepancies in the data.

The parameter for the back arch resulted in 20 false positives. This is attributed to the system detecting if there is arch in the back at all, as opposed to the expert desiring a more pronounced back arch. The grip width parameter resulted in 17 false negatives. It is possible that this occurred because the system provided the user with feedback indicating that they were within the ideal range immediately after making an adjustment, thereby providing negative feedback for any small modifications to their grip or shoulder width during the exercise. The left shoulder abduction angle had 13 false negatives as opposed to the right shoulder abduction angle which had 50 false negatives. By utilizing the same algorithm for both angles, we observed a higher degree of accuracy in the left shoulder abduction angle compared to the right shoulder abduction angle. This could potentially be caused by the distortion generated by the wide-angle camera, impacting the system's accuracy. Additionally, the distortion is present in the saved videos, thereby potentially making it challenging for the expert to provide judgement. The bar tilt parameter resulted in 35 false positives which may have been caused by any misalignment during the initial placement of the markers to the gloves.

B. *Limitations*

The primary limitation our team faces is our planning process. We initially created a Gantt chart to establish a schedule for the two-year capstone project. However, we gradually deviated from the schedule and failed to adjust for lost time. When we began integrating all of our processes, we encountered challenges integrating our code, and we realized that we did not budget enough to purchase a better processor. Consequently, we had to spend time optimizing our algorithm instead of collecting data, compromising the project's progress.
As a result, we submitted our IRB late, limiting us to collect only one round of data for analysis and review by a single expert. Instead of optimizing the algorithm, we should have focused on data collection and iterated the project to improve GymSense's accuracy.

VI. Conclusions

In conclusion, this study aimed to develop a system that could aid novice lifters in improving their bench press form. The system used sensors to detect and provide feedback on five parameters: Arch, Grip Width, Left Angle, Right Angle, and Tilt. The results showed that the overall accuracy of the system was 72.16%, with the left angle being the most accurately measured parameter and the right angle and tilt having the largest errors. Although the system has room for improvement, the results are promising, and the system has the potential to aid novice lifters in improving their form. Further research and development could lead to a more accurate and effective system.

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