TEAM STRIKE: Punching Bag with Vectornav Final Paper

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**Note: The overview and team results is the same for the entire group*

OVERVIEW

Our project aims to understand the motion and dynamics of sports actions, specifically the result of the interactions between players and equipment. We utilized an IMU to gather precise information on the forces exerted by players onto their equipment and the subsequent movement of the equipment. By analyzing this data, we can gain insights into the underlying physics that govern sports equipment interactions during play and any improvements players can make to be more effective in their play.

As one of our group members is a black belt in Karate, we decided to look into the differences between an experienced martial artist and a beginner when it comes to throwing a punch. An IMU was strapped to a punching bag to record data from each strike, allowing for the analysis of datasets alongside trial videos to determine what defines a good punch Ultimately, we wanted to understand how factors such as technique would affect performance.

The project was inspired by studies that analyze the dynamics of sports equipment, such as simulations of rugby ball trajectories [1]. Data was collected using a VectorNav VN-100 IMU, following a procedure approved by the university's gym and carried out inside Marino. The IMU was attached to a punching bag, adjusted for height differences among participants, with the x-axis aligned vertically, the z-axis facing the direction of the punch, and the y-axis sideways as shown in Figure 1. For safety reasons, the IMU was mounted on the punching bag instead of on the individuals performing the punches.

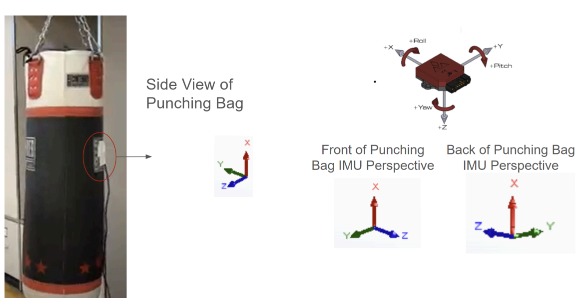


Fig. 1. Orientation of IMU attached to punching bag

A ROSbag of IMU data and corresponding videos were collected as each participant punched five times, resulting in a total of 25 punches for analysis, as depicted in Figure 2. The analysis focused on motion trajectory, linear and rotational velocity, force exerted on the bag, and kinetic energy, with particular attention to differences between novice and expert performances.

One out of five participants was considered an expert. The study progressed through three planned levels: confirming the setup's ability to capture acceleration (Level 1), reconstructing the bag's path (Level 2), and analyzing distinct motion signatures between novices and experts (Level 3). Originally intended to extend to a hockey stick and a rugby tackling pad, the project's scope was narrowed to only the punching bag data following an accident with the IMU and subsequent time constraints.

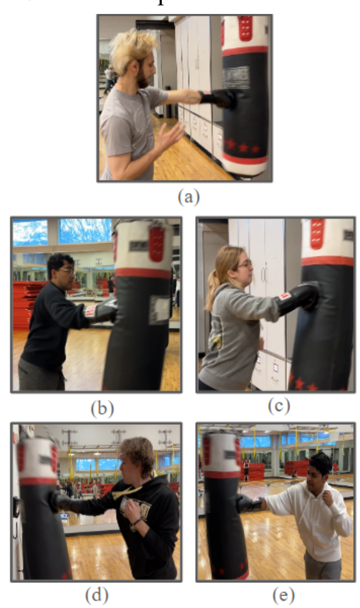


Fig. 2. Visual of the experimental set up with five punchers; (a) Shaked (Pro) with novices (b) Satish, (c) Jessica, (d) Andrew, and (e) Sakib

TEAM RESULTS

With the collected data, everyone on the team took a separate aspect of the data to analyze. Each analyzed dataset could then be used to compare between the amateurs and the professional to see if there is a noticeable difference between them. This analysis would be helpful to sport novices, looking to improve or keep their form safe. The different aspects of the data analysis were the linear velocity and acceleration, impulse generated by each punch, punching bag trajectory, the force exerted on the bag, the rotational velocity of the bag, and the kinetic energy of the bag.

In this preliminary study, the trajectory of the punching bag was mapped for each participant's trials to identify any significant differences in the collected data. 2D animations of the bag's movement in the x-z plane, the intended plane of motion as the bag/IMU swings around the y-axis, showed no major differences in trajectory across trials. However, all trials exhibited a similar pattern: a smooth parabolic path initially, followed by rapid jumps between points on the curve, likely due to the VectorNav's limited sampling rate, which was considered in subsequent analyses.

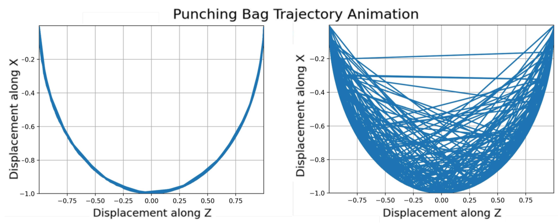


Fig. 3. Trajectory Mapping of the X-Z plane

Computing the acceleration plot was the foundation of our analysis. Force, impulse, and trajectory are derived from acceleration of the bag.

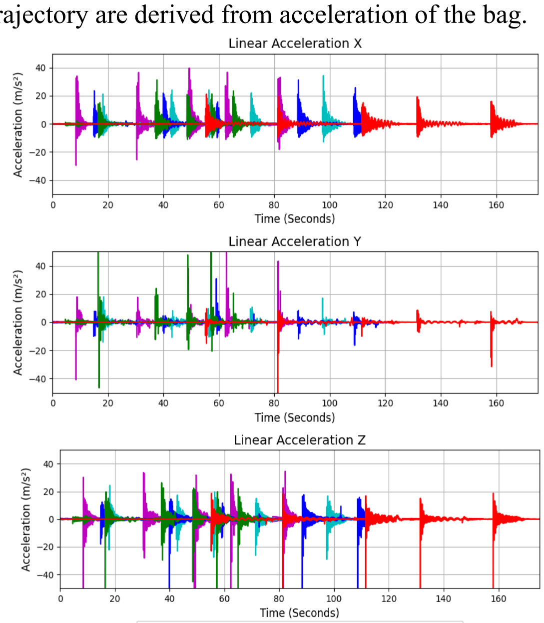


Fig. 4. Linear Acceleration in X,Y,Z for all punchers

These values come from the IMU's VNYMR acceleration components. Figure 4 shows that each puncher executed five punches. Shaked's punches appear to be the most accelerated among the group.

The angular velocity of the punching bag was used to determine how close each punch was to the middle of the bag. If a punch was off-centered, the punching bag would spin around its vertical axis. A comparison of a punch that caused the bag to spin a lot versus one that didn't cause it to spin much at all is shown below in Figure 4. Because the pro was able to hit the center of the punching bag more consistently, the angular velocity of the bag after his punches were on average much lower than all of the amateurs.

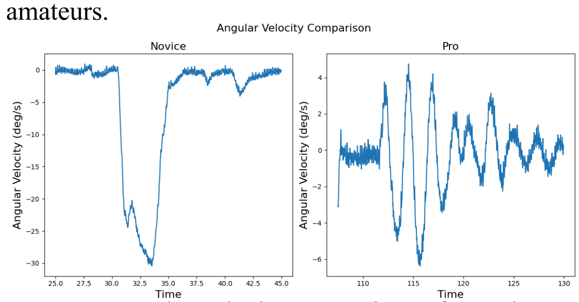


Fig. 5. Angular velocity comparison of a novice's punch (left) versus an expert's (right).

Next, the force exerted by each punch was calculated by multiplying the mass of the punching bag with the linear acceleration for each individual. Shaked, identified as the "expert" due to his extensive martial arts background, along with Andrew, displayed the highest force impacts on the punching bag, according to Figure 6-7. We further examined the components of force in each direction for each participant, revealing that Shaked was able to direct a significant amount of his force towards the z-direction compared to the rest of the team.

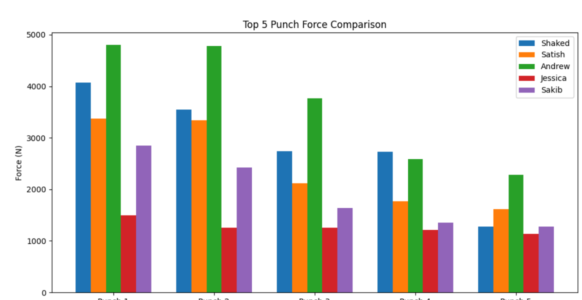


Fig. 6. Five Trial Punch force comparison.

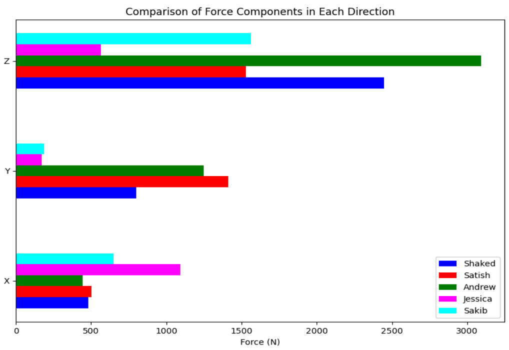


Fig. 7. Average Punch force comparison.

Using the video recording of each punch, the time of impact for each punch was able to be determined. This was used along with data from the accelerometer to calculate the impulse. The force values were calculated by multiplying the mass of the punching bag by the acceleration in all three axes measured by the IMU. Then, the force values were integrated over the duration of the impact time to calculate impulse. The calculated impulses generated by each punch are shown below, in Figure 8.

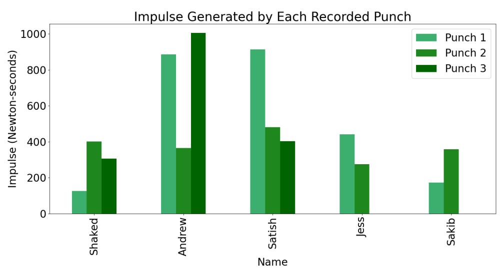


Fig. 8. Impulse generated by each recorded punch.

These results are interesting, as the impulse generated does not follow a trend based on punching experience. Shaked, who was designated as the "pro", has a lower generated impulse than many of the other members. While this analysis includes acceleration in all three directions, a similar trend is found when analyzing the impulse generated in the z-direction.

Both linear and rotational kinetic energy were considered. The results show that most of the kinetic energy comes from linear acceleration (from 6000 to 12000 J), and not much from rotational (from 8 to 20 J). It also demonstrates the idea that an expert punch has a more linear path (less rotation about the x-axis), since the expert graph shows less of a spike there. However, the total kinetic energy between the two was not too different - this value was a sum of linear and rotational kinetic energy in all axes.

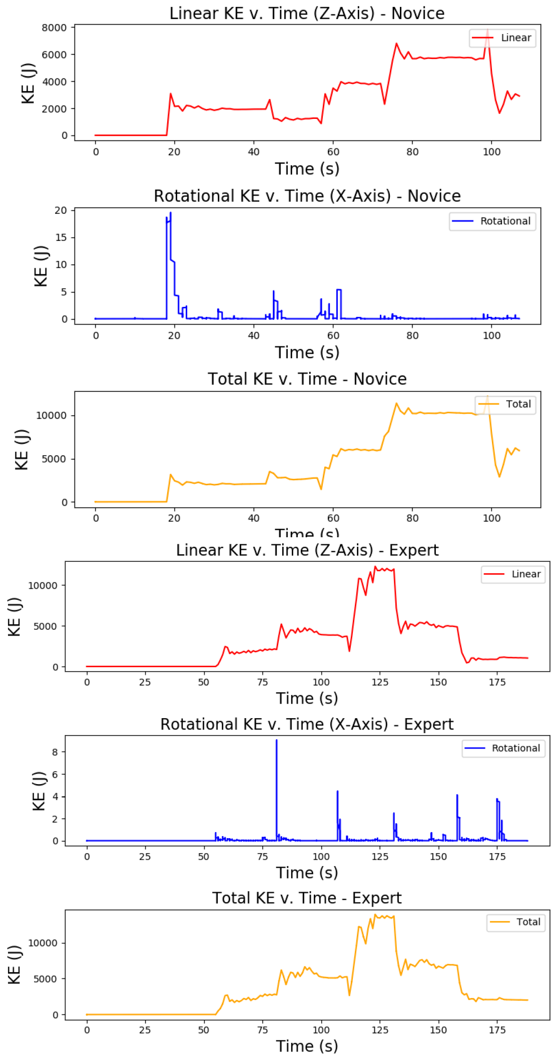


Fig.9. Linear, rotational, and total kinetic energy for novice (top) and expert (bottom).

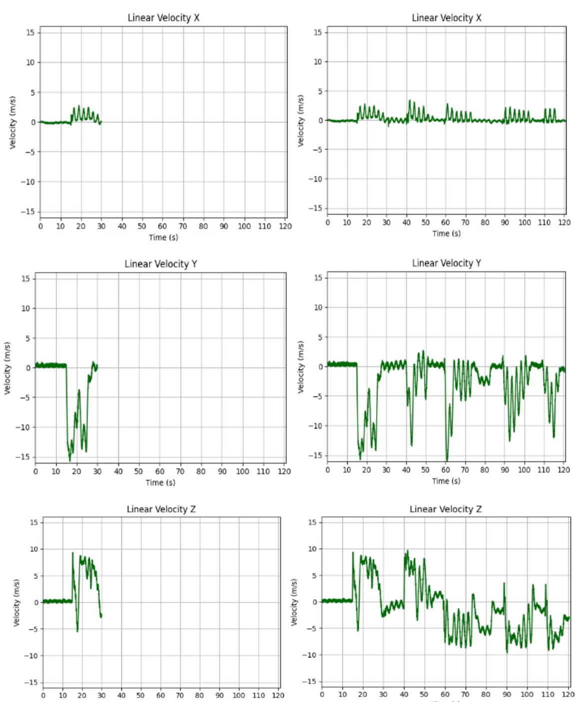
Several trends emerged in our data distinguishing novices from experts—force, kinetic energy, rotational velocity, and consistency. Despite low sampling rates and safety concerns limiting definitive conclusions, notable differences were observed. For example, a professional's punches showed greater consistency and accuracy, as demonstrated by Shaked's ability to strike the bag head-on with minimal extraneous motion. In contrast, force output was more closely correlated with participant size rather than technique. This information can guide novice training to ensure safe form and help achieve their goals.

LINEAR VELOCITY INDIVIDUAL ANALYSIS

In this project, I engaged significantly in both the experimental and media production aspects. I participated as one of four novice punchers in 25 trials. This gathered comparative data against Shaked's expert performances on the punching bag.

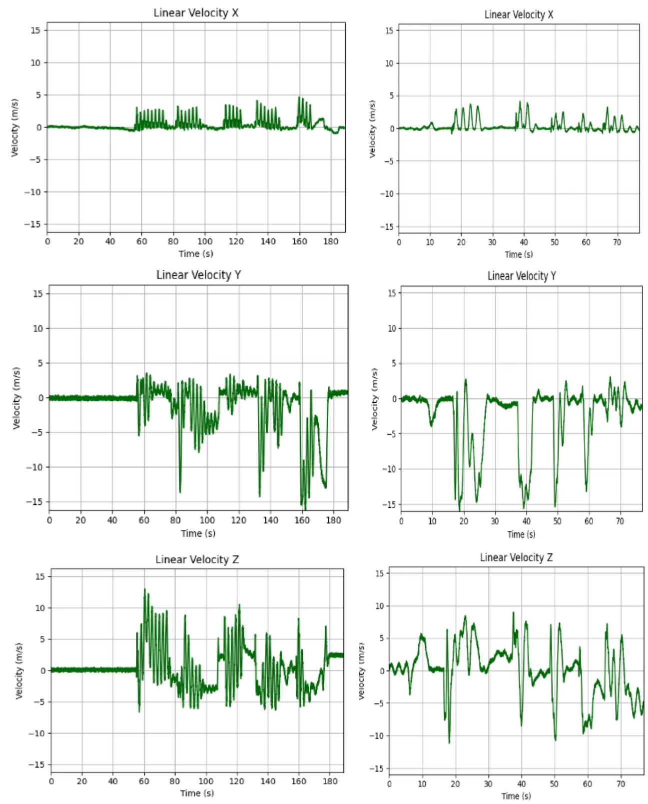
For the media component, I spearheaded the video production process. I was responsible for editing the video, which involved filming the trial punches, compiling the footage, and integrating it into a cohesive teaser video. I requested voiceovers and data plots from my group members, which I then meticulously edited into the final video to ensure it was both informative and professionally presented.

In terms of data analysis, my responsibilities were tailored to accommodate my extensive media duties. I handled the generation of linear acceleration plots and the calculation of linear velocity using two methods. I also created animations that displayed these metrics side by side, syncing the peaks of the graphs with the timing of the punches. This animation was featured in our teaser video, providing a clear and dynamic visualization of our findings.



(a) (b)

Fig.10. Linear Velocity of Sakib's (Novice) punches with (a) showing animation of trial 1 punch and (b) displaying graph animations of all 5 punches.



(a) (b)

Fig.11. Linear Velocity in x, y, and z of (a) Shaked's "pro" punches and (b) Satish's "novice" punches

Figures 10b and 11b depict the linear velocity of a punching bag post-impact by novice individuals, while Figure 11a illustrates the velocity following punches delivered by Shaked. Notably, all the x-axis velocity graphs display a similar trend; this observation aligns with the information presented in Figure 1, where the vertical direction is associated with the positive x direction, and the motion of the punching bags post-punch is consistently in this orientation.

In the y-velocity plot of Figure 10b, a regular oscillation pattern is evident, although the peak velocities seldom exceed -10 m/s, indicating punches of moderate intensity. Conversely, Figure 11b's y-velocity subplot exhibits pronounced spikes and greater velocity variations, which suggest that the punches imparted higher force, resulting in more pronounced swinging of the bag. However, Satish's punches, observed firsthand, resulted in the bag swinging erratically in various directions, reflecting a lack of control.

Figure 11a's y-velocity graph, capturing Shaked's punches, shows oscillations more subdued than Satish's but more pronounced than Sakib's, indicating a balance of power and precision crucial in competitive sports. This balance prevents excessive force that can compromise accuracy and cause injury, as evidenced by Shaked's consistent, powerful punches with velocities exceeding -15 m/s. Furthermore, the z-velocity plots reveal that while Sakib (Figure 10b) and Satish (Figure 11b) show declining velocity trends, Shaked's (Figure 11a) maintains a steady oscillation between positive and negative velocities, suggesting the punching bag swings like a simple pendulum when struck by Shaked, demonstrating the control needed for effective punches.

Linear velocity was calculated using data from the IMU's gyroscope, specifically from the VNYMR string, factoring in a radius of rotation. This radius was estimated to be 0.3 meters, measured using a phone as a makeshift ruler.

$$v = r * \omega \qquad (1)$$

The formula applied to determine the linear velocity involved tangential velocity (v), radius of rotation, and angular velocity (ω, in radians per second). To compute ω, it was necessary to first convert the gyroscope data from quaternion format to euler angles, representing the rate of change in these angles. This conversion was essential for accurately calculating the angular velocity from the IMU readings.

$$q = (q_w, q_x, q_y, q_z) \qquad (2)$$

$$\vec{\omega}' = (0, \omega_x, \omega_y, \omega_z) \qquad (3)$$

Equation 2, using quaternion format, operates in four-dimensional space, whereas Equation 3 uses a zero placeholder to adapt to the three-dimensional Euler angles. The aim is to convert the quaternion-based vector in Equation 2 into the three-dimensional vector format of Equation 3, used for Euler angles.

$$\phi = \operatorname{atan2}(2(q_w q_x + q_y q_z), 1 - 2(q_x^2 + q_y^2)) \quad (4)$$

$$\theta = \operatorname{asin}(2(q_w q_y - q_z q_x)) \qquad (5)$$

$$\psi = \operatorname{atan2}(2(q_w q_z + q_x q_y), 1 - 2(q_y^2 + q_z^2)) \quad (6)$$

Equation 4 through 6 are the equations used to convert quaternion angles to Euler angles represented in ϕ (roll), θ (pitch), and ψ (yaw).

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi)/\cos(\theta) & \cos(\phi)/\cos(\theta) \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \quad (7)$$

Equation 7 is the matrix multiplication needed to obtain the angular velocity vector **ω** in terms of rate of changes of the Euler angles ($\dot{\phi}$,$\dot{\theta}$,$\dot{\psi}$). This gives angular velocity and then multiplied by radius gives linear velocity.

Another method to derive forward linear velocity is by integrating acceleration data from the accelerometer over time.

$$v(t) = \int a(t)dt \qquad (8)$$

Integrating accelerometer values over time to calculate linear velocity can introduce significant errors due to drift and noise accumulation. Conversely, using gyroscope data to compute linear velocity through angular velocity is generally more stable and accurate. This makes gyroscope-based measurements particularly reliable for short-term applications, such as recording the velocity of punches on a punching bag in multiple trials.

CONCLUSION

The linear velocity analysis revealed notable differences in the punching technique between the novice and expert participants. Using gyroscope data, the expert, Shaked, demonstrated a consistent linear velocity averaging -15 m/s, while novices showed more variable velocities with peaks seldom exceeding -10 m/s. From the team analysis, it was observed that the expert's punches exerted greater force on the punching bag, with peak forces in trials averaging significantly higher than those of the novices. Overall, the project's findings emphasize the importance of technique and control in sports performance, highlighting how expert guidance can enhance both safety and effectiveness in training.

APPENDIX

Supplementary content in the following hyperlinks.

1) Punching Bag Trials
2) Linear Velocity/Acceleration Animation Plots
3) Code from Github

REFERENCES

[1] Seo, K., Kobayashi, O., Murakami, M. et al. Simulation of the trajectory of a punted rugby ball taking into account the asymmetrical pressure distribution caused by the seams. J Vis 13, 97–105 (2010). https://doi.org/10.1007/s12650-009-0019-0